INVESTIGATION OF THE PHYSICAL CONDITIONS CONTROLLING SPAWNING OF OYSTERS AND THE OCCURRENCE, DISTRIBUTION, AND SETTING OF OYSTER LARVÆ IN MILFORD HARBOR, CONNECTICUT

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INTRODUCTION

The primary purpose of this investigation is to show the close relationship that exists between physical conditions and the success or failure of oyster production in inshore waters. It is hoped that the analysis of conditions in Connecticut waters and the determination of the predominating factors that control oyster propagation there may serve as the basis for the development of scientific oyster culture in our extensive coastal waters. To accomplish this, it is essential that we have a thorough knowledge of the oyster in every stage of its development and a greater understanding of the influence of each physical and biological factor on the egg, embryo, larvæ, spat, and adult. In the cultivation or control of an aquatic animal such as the oyster, the response of the organism to changes that occur in its environment is not only of scientific interest but may be of great practical importance. The plan of the investigations carried out at Milford, Conn., during the summers of 1925 and 1926 was to study the effect of the physical conditions on the oyster and oyster larvæ in this typical location, the results of which would serve as the basis for analyzing and understanding the conditions found in other oyster-growing regions.

The most important problem that presented itself was the analysis of the causes of the great variations that occur in the annual production of seed oysters on an entire natural bed as well as on the cultivated oyster beds. A good example of this is the Bridgeport natural bed, which, according to Collins (1889), produced 115,000 bushels of oysters in 1887, 31,000 in 1888, and 3,500 in 1889, most of which were seed oysters. On the cultivated beds of Connecticut similar fluctuations in seed production during the last three years are representative of the experiences of the industry since the initiation of oyster culture. For instance, the production of seed oysters here ranged from over 1,000,000 bushels in 1925 to virtually none in 1926 and 1927. Through a detailed study of the conditions in Milford Harbor, it was hoped that an understanding of this phenomenon might be obtained. The objects of this investigation were to determine—

1. The principal factors that influence and control the spawning of oysters.
2. The occurrence and distribution of the oyster larvæ.
3. The zones in which setting or attachment of the larvæ takes place.
4. The conditions responsible for the occurrence of great annual fluctuations in the intensity of setting or production of seed oysters.

These studies were conducted under the direction of Dr. Paul S. Galtsoff, in charge of oyster investigations, to whom the author is deeply indebted for advice in the course of the work and for criticism of the manuscript.

The author wishes to acknowledge his appreciation of the valuable and cordial cooperation rendered by the North Atlantic Oyster Farms (Inc.) in carrying on these investigations, and especially the help, suggestions, and information given by W. H. Raye, Capt. Charles E. Wheeler, and A. E. Loring, of that company, relative to various studies of the oyster situation and for generously supplying oysters, laboratory facilities, men, and boats for this work. Valuable assistance was received from H. A. Marmer, of the United States Coast and Geodetic Survey, in the studies of the tides and currents, and from the United States Weather Bureau and Geological Survey in supplying climatological and river-discharge data.

METHODS AND EQUIPMENT

A small laboratory was established at the plant of the Connecticut Oyster Farms Co., at Milford, Conn., where suitable arrangements could be made for setting up tide and temperature recording apparatus and for boating operations. In Milford Harbor and the adjacent inshore waters of Long Island Sound six stations were established, as shown in Figure 1. These were visited regularly with a small cruiser equipped for the collection of water and plankton samples and for making observations of general physical conditions.

Water temperatures at the surface and bottom were taken at each cruising station by means of a Negretti and Zambra deep-sea reversing thermometer, and, in addition, a long-distance thermograph was set up at Station 2, which recorded continuously the water temperatures on the bottom in the harbor.

In collecting water samples for the determination of salinity and pH, a Greene-Bigelow water bottle was lowered over the side by means of a meter wheel and Lucas sounding machine. The samples were titrated in the usual way, using silver nitrate against the international standard sea water and calculating the salinities by means of Knudson's (1901) hydrographical tables. For the determination of the hydrogen-ion concentration of the water, the colorimetric method was employed, using cresol red and brom-thymol blue as indicators. No correction for salt error has been made for the figures that are given. All the observations fall within the range of the indicator cresol red.

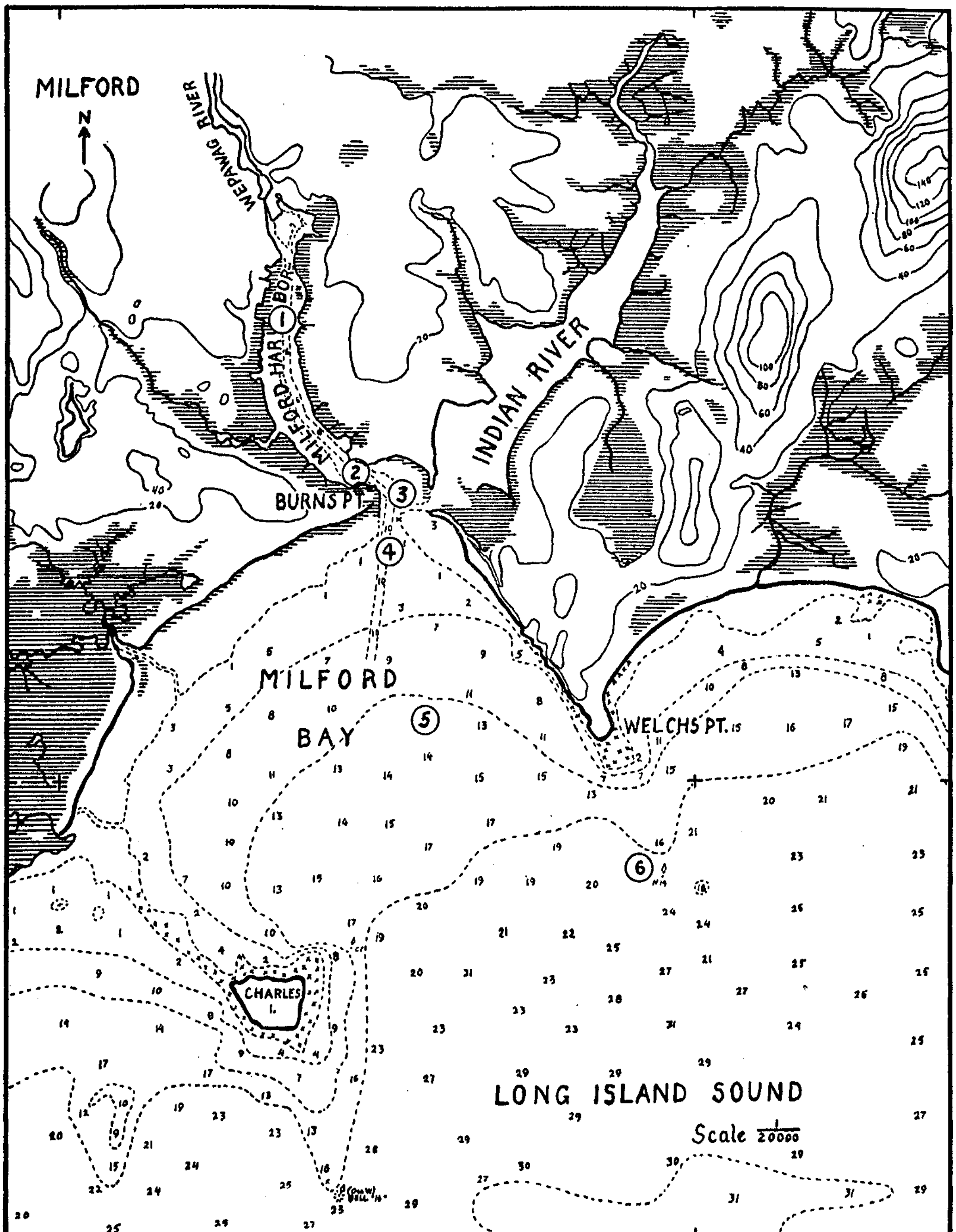

FIGURE 1.—Location of stations and hydrographical features of Milford Harbor and vicinity

In studying the tides and currents several devices were used. At Station 2 an automatic tide gauge was put in operation, whereby a continuous record of the rise and fall of tide in Milford Harbor was obtained. The velocity and direction of the tidal currents at various depths and stages of the tide were determined by means of Eckman and Price current meters. In order to determine the drift or general movement of the water along the Connecticut shore of Long Island Sound, 500 drift bottles with drags were released from several localities, and of these, over 300 have been recovered.

The most important procedure was the collecting and examining of plankton collections to determine the presence of oyster larvæ. The method employed was essentially the same as that used by Churchill and Gutsell (1920; unpublished manuscript, United States Bureau of Fisheries) for determining the abundance of oyster larvæ. The results obtained by this method are quantitative and of much greater value than those obtained by drawing a tow net through the water.

At each station, 50-gallon samples were taken at the surface and bottom and occasionally at various depths. By means of a rotary bronze pump with 50 feet of rubber hose weighted at the intake end a definite quantity of water was pumped on deck and strained through a net of No. 20 bolting silk. The plankton collected was washed down into a quart jar, labeled, and preserved in 10 per cent formalin. In the laboratory, the contents of each jar was washed through a series of sieves covered with Monel-metal wire of Nos. 80, 100, 150, 200, and 270 mesh. This procedure served to classify the oyster larvæ according to their size and greatly simplified microscopic examination of the samples by dividing them into several portions. The plankton collected in each sieve was washed into watch glasses, and the number of oyster larvæ was determined by direct count under the microscope.

The setting of the oyster larvæ was studied in 1925, 1926, and 1927 by arranging several types of stationary and floating spat collectors in various positions, according to the depth of water, tides, and currents. For spat collectors, brush, glazed tiles, tar paper, clam, scallop shells, and oyster shells were used, the latter being set out in lath crates and wire baskets.

TOPOGRAPHY

Milford Harbor is situated on the Connecticut shore of Long Island Sound and lies about halfway between two great oyster-producing centers—Bridgeport and New Haven. The general topographic and hydrographic features of the harbor and surrounding territory are shown in Figure 1. In this discussion, the term "Milford Harbor" is applied only to the area above the stone breakwater at Burns Point, which, on the hydrographic charts, is labeled "Wepawaug River." This small body of water covers approximately 80 acres, about half of which is exposed at low tide. It is a small but typical oyster-producing harbor, and in former times the entire area was a natural bed of oysters. In this nearly inclosed basin, the brackish water of Long Island Sound mixes with the fresh water from two small streams—the Wepawaug and Indian Rivers—producing ideal conditions for oyster growth and propagation.

As a result of overfishing, the harbor was found to be virtually devoid of oysters, so that it was necessary to restock it before carrying on the experiments. The

Connecticut Oyster Farms Co. generously supplied a sufficient quantity of large oysters to establish two spawning beds, one of which was located on the flats and the other in the channel. Since at present these waters are unpolluted to any serious degree, it was possible, by the rehabilitation of this small harbor, to study the oyster in an environment very similar to that in which it thrived in years past.

Milford Harbor is but one of the many inshore areas that border and empty into Long Island Sound, and its topography would not be complete without a description of this adjoining large body of water.

Long Island Sound is a partially inclosed basin having a length of about 80 nautical miles and a depth averaging 65 feet. Its general shape is that of a double convex lens with the broadest portion at a point just southeast of New Haven, where its width is about 16 miles. From this point to the eastward the width of the Sound decreases gradually until it is about 8 miles wide at its mouth, where it receives the water from Block Island Sound and the Atlantic Ocean. To the westward of New Haven the shore lines also converge until they are less than a mile apart at the head of the Sound or upper entrance to New York Harbor.

The longitudinal axis of the Sound lies in a northeast and southwest direction and is about at right angles to the rivers emptying into it from the north. The two principal drainage basins discharging into the Sound are those of the Connecticut and Housatonic Rivers, the valley of the former extending about 250 miles to the north and of the latter, 90 miles.

The water in the Sound is a mixture of the salt water brought in by the tides from the ocean with the fresh water discharged by the rivers, its average salinity for the year, as determined by Galtsoff (unpublished report), ranging from about 24 parts per thousand at Hell Gate to 29 at its mouth. As a result of the tides, the level of the Sound changes constantly, and large inshore areas, covering thousands of acres, are regularly flooded and exposed at times of high and low water. The location, extent, and contour of these flood grounds determines, to a noticeable degree, the differences that are found in the physical conditions in each of the various inshore areas, such as Milford Harbor, and in the various parts of the Sound.

PHYSICAL CONDITIONS

GENERAL

A study of the early location of the natural oyster beds and shell deposits along the coast of Long Island Sound clearly indicates that certain regions were more favorable than others for the growth and propagation of the oyster. The favorable regions, for the most part, were found to lie in the coves, bays, and estuaries and were all similar in structure, consisting generally of a partially inclosed basin, which received fresh water from the land and salt or brackish water from the place into which it emptied. In these bays and harbors the natural beds extended from nearly the upper limit reached by the brackish water to some distance outside of the entrances. This is well illustrated in Figure 2, which is taken from an old map of the oyster grounds of Connecticut published in 1889. The location and extent of the natural beds clearly defines the regions in which the physical conditions were most favorable for the growth and propagation of the oyster. If we examine these areas carefully,

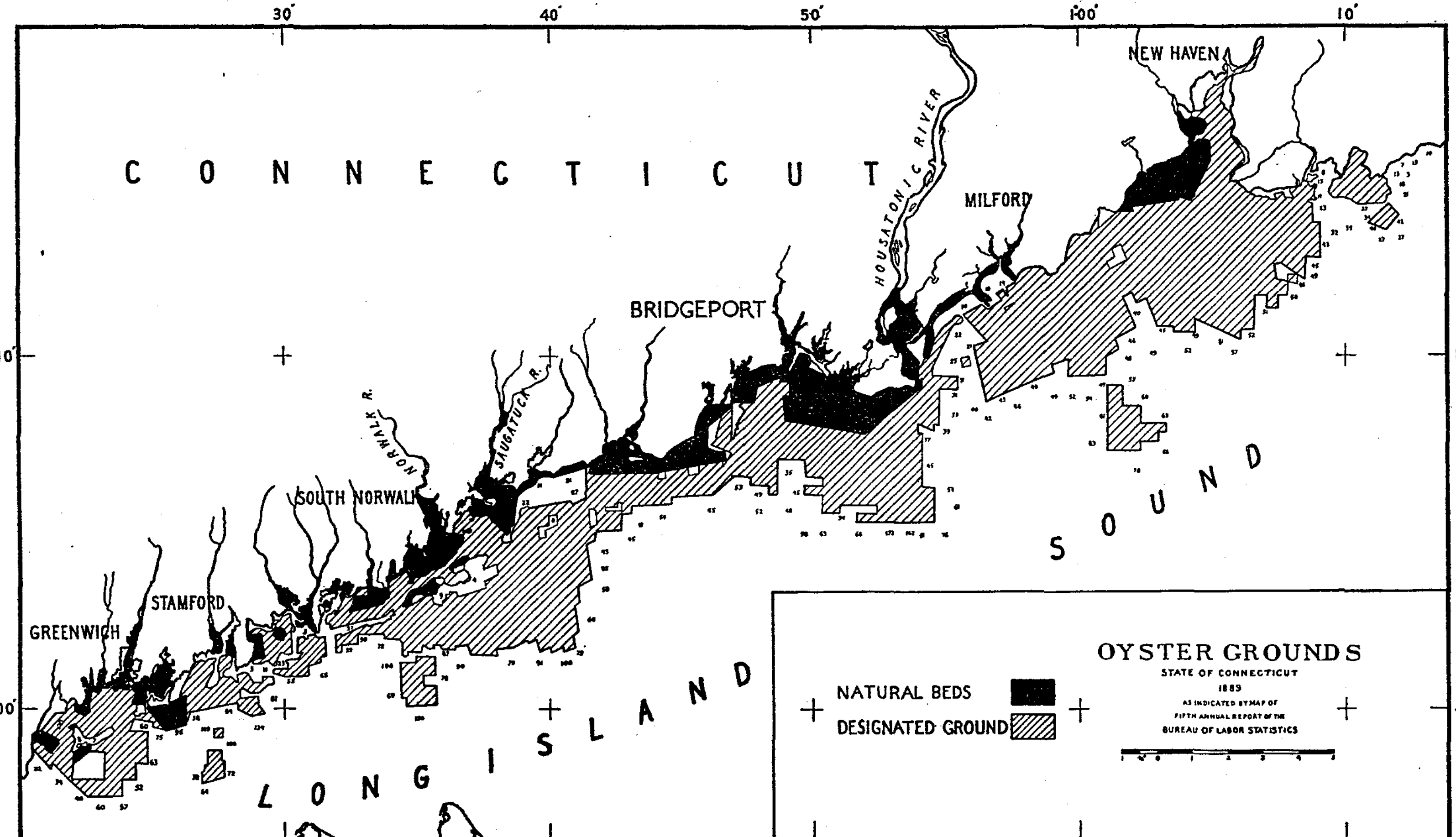
CONNECTICUT
LONG ISLAND SOUND
NEW HAVEN
MILFORD
HOUSATONIC RIVER
BRIDGEPORT
SAUGATUCK R.
NORWALK R.
SOUTH NORWALK
STAMFORD
GREENWICH
NATURAL BEDS
DESIGNATED GROUND
OYSTER GROUNDS
STATE OF CONNECTICUT
1889
AS INDICATED BY MAP OF
FIFTH ANNUAL REPORT OF THE
BUREAU OF LABOR STATISTICS
30′
40′
50′
1°00′
10′
41°00′

FIGURE 2

we find that at several points between the upper and lower boundaries of the natural beds in each section the productivity and abundance of the oysters show wide variations. As a general rule, oyster growth and seed production are best in a zone about halfway between the upper and lower limits of a natural bed and least at the extremes, which can be correlated with variations in the physical conditions found in different parts of the bed. However, if we take the natural beds as a whole, or the cultivated beds, we find great fluctuations in the quantity of seed oysters that they produce from year to year. Their production often ranges from over 1,000,000 bushels, as was the case in 1925, to virtually none, as in 1926 and 1927. The study and comparison of the physical conditions in 1925 and 1926 was made in order to determine the factors responsible for these annual fluctuations in seed-oyster production.

The potential value of any body of water for the propagation, growth, or fattening of oysters is determined largely by the physical and chemical conditions that exist there. In some localities these conditions are more or less constant, while in others they undergo considerable variation. Each region, however, has certain physical characteristics of its own, and these are representative of the combined influence of the climatological, hydrographical, and physiographical conditions found there. In Milford Harbor and vicinity there is a great range of variation in a comparatively short distance; and since it is a favorable location for the production of three important shellfish—the oyster, quahaug, and soft clam—the various factors will be discussed in detail in order that they may serve as the basis for comparison with other regions.

TEMPERATURE

In the environment of the oyster, water temperature is the most important factor, as it controls, either directly or indirectly, the growth and reproduction of the organism. It directly affects the physiological processes of the oyster, such as feeding, respiration, development of the gonads, spawning, etc., while indirectly it influences, to a great extent, the growth and abundance of the microscopic forms that constitute the food of the oyster and oyster larvæ.

The water temperature in Milford Harbor is the resultant of the interaction of the various factors that can be placed in two major groups—the climatological and the hydrographical. The chief climatological factors affecting water temperature are (1) solar radiation, (2) air temperature, (3) precipitation, (4) wind, and (5) percentage of sunshine. The chief hydrographical factors, in order of their importance, are (1) tide, (2) river discharge, (3) tidal currents and circulation, and (4) depth of water.

The relative importance of any one of these factors can be discussed only in a general way because its effect on water temperature depends largely on its relation to one or more of the remaining factors.

In Figure 3, the mean daily temperatures of bottom water are shown for July and August of 1925 and 1926 and cover the period when spawning and setting of oysters occur in Connecticut waters. The figures are taken from the records of the thermograph placed in the harbor at Station 2, the average for each day being determined by means of a planimeter. The fluctuations in water temperature that occurred during these two summers are typical for estuaries and shallow inshore bodies of water, where there is considerable variation according to the day and even the hour.

In beginning our analysis of the data, we find that the mean temperature for the 2-month period was 20.3° C. for 1925 and 19.7° C. for 1926, showing a slight annual difference of less than 1°. The monthly and daily averages, however, show greater differences between the two years and are of greater importance, as will be shown later because of the effect of temperature on (1) the ripening of the gonads and (2) the spawning reaction of the oyster. In 1925 the mean monthly water temperature during July was 19.7° C., while in 1926 it was 17.8° C., or 1.9° lower. During August, 1925, the monthly mean was 20.8° C. and in 1926, 21.6° C. As can be seen from Figure 3, the water temperature on certain days was above 20° C., and we are interested in discovering the difference between the two years in relation to this point, because it has been found by previous observation that spawning of the oysters occurred after the water had reached this temperature. In July, 1925, there were

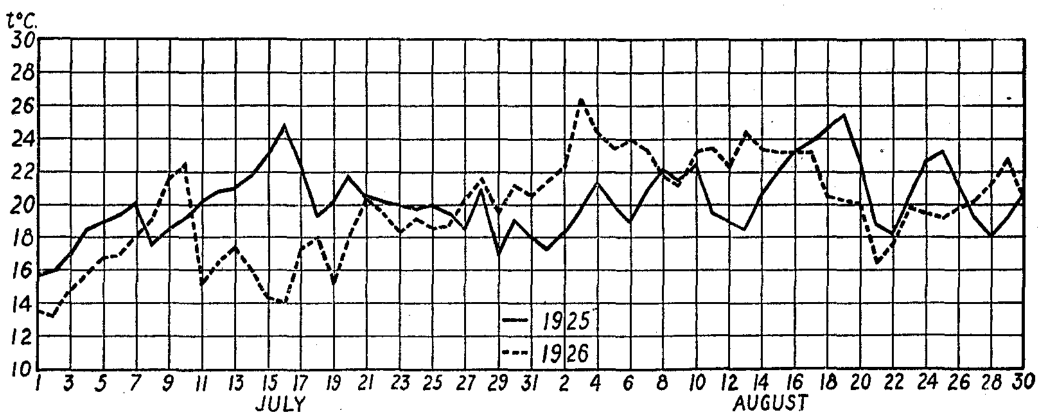

FIGURE 3.—Mean daily bottom temperature, ° C., at Station 2, Milford Harbor. Computed from thermograph records

15 days when the temperature was above 20° C. and 16 when it was below, while in 1926 there were only 7 days when it was above and 24 days when it was below. In August, 1925, there were 19 days when the water temperature was above 20° C. and 12 when it was below, while in 1926 it was above this point for 24 days and below only 7 days. These data are presented in the following table, together with the highest and lowest water temperatures for each month.

TABLE 1.—*Fluctuations in daily water temperature from 20° C.*

Month	Number of days		Highest daily temperature	Lowest daily temperature
	20° C. and above	Below 20° C.		
July, 1925	15	16	24.8	15.8
July, 1926	7	24	22.4	13.2
August, 1925	19	12	25.4	17.4
August, 1926	24	7	26.4	16.5

Although these data refer to the inshore areas, they reflect the trend of conditions in the Sound, where the water generally is from 2 to 3 degrees lower than the daily average in the harbor. This decrease in temperature, which is found as we leave Station 1 in the upper part of the harbor and go out to Station 6 in the Sound, is shown clearly by Figure 4. In this figure the distribution of temperature is shown for July 15, 1925, when the water in the harbor and Sound was unusually warm for this time of the year. The temperature records at Station 2 in the harbor are the most complete, however, and have been analyzed and are presented in Tables 2 and 3, which give the maximum, minimum, mean, and range of temperature for each day of the summers of 1925 and 1926.

TABLE 2.—*Water temperatures at Station No. 2, 1925, in °C.*

Date	July				August			
	Extremes		Daily		Extremes		Daily	
	Maximum	Minimum	Mean	Range	Maximum	Minimum	Mean	Range
1	17.5	15.0	15.8	2.5	19.0	15.0	17.4	4.0
2	19.5	15.0	16.0	4.5	19.5	17.0	18.2	2.5
3	21.0	16.0	17.0	5.0	23.0	18.0	19.8	5.0
4	21.5	17.0	18.5	4.5	24.5	19.0	21.4	5.5
5	22.0	17.5	19.0	4.5	20.5	18.5	20.0	2.0
6	23.0	15.5	19.4	7.5	20.0	18.5	19.0	1.5
7	22.5	17.5	20.2	5.0	22.5	20.0	20.8	2.5
8	20.0	17.0	17.6	3.0	25.0	21.0	22.2	4.0
9	21.5	17.5	18.5	4.0	22.0	21.0	21.5	1.0
10	20.0	18.5	19.2	1.5	25.0	20.5	22.4	4.5
11	22.5	19.5	20.2	3.0	22.0	18.0	19.5	4.0
12	22.5	18.0	20.8	4.5	20.5	18.0	19.0	2.5
13	23.0	18.0	21.0	5.0	20.5	18.0	18.5	2.5
14	25.0	18.0	21.8	7.0	23.0	19.0	20.6	4.0
15	25.0	20.0	23.0	5.0	23.0	21.0	22.0	2.0
16	27.0	20.5	24.8	6.5	25.5	22.0	23.2	3.5
17	26.5	20.0	22.5	6.5	27.0	23.0	23.8	4.0
18	24.0	17.0	19.4	7.0	28.5	22.0	24.6	6.5
19	24.0	16.5	20.2	7.5	29.0	23.0	25.4	6.0
20	26.0	19.0	21.8	7.0	27.0	20.0	22.8	7.0
21	21.5	20.0	20.5	1.5	19.5	15.5	18.8	4.0
22	22.0	19.5	20.2	3.5	20.0	16.0	18.2	4.0
23	23.5	19.0	20.0	4.5	21.0	19.0	20.2	2.0
24	22.5	19.0	19.8	3.5	23.0	21.0	22.6	2.0
25	22.5	18.5	20.0	4.0	24.0	21.5	23.2	2.5
26	21.0	18.5	19.6	2.5	24.5	18.0	21.4	6.5
27	20.5	18.0	18.5	2.5	20.0	16.0	19.2	4.0
28	23.0	19.0	21.0	4.0	20.5	15.5	18.0	5.0
29	21.5	16.0	17.0	5.5	23.0	17.0	19.2	6.0
30	20.0	17.5	19.2	2.5	23.0	19.0	20.6	4.0
31	20.0	16.5	18.0	3.5	24.0	19.0	21.8	5.0
Monthly mean	22.3	17.9	19.7	4.4	22.9	19.0	20.8	3.8

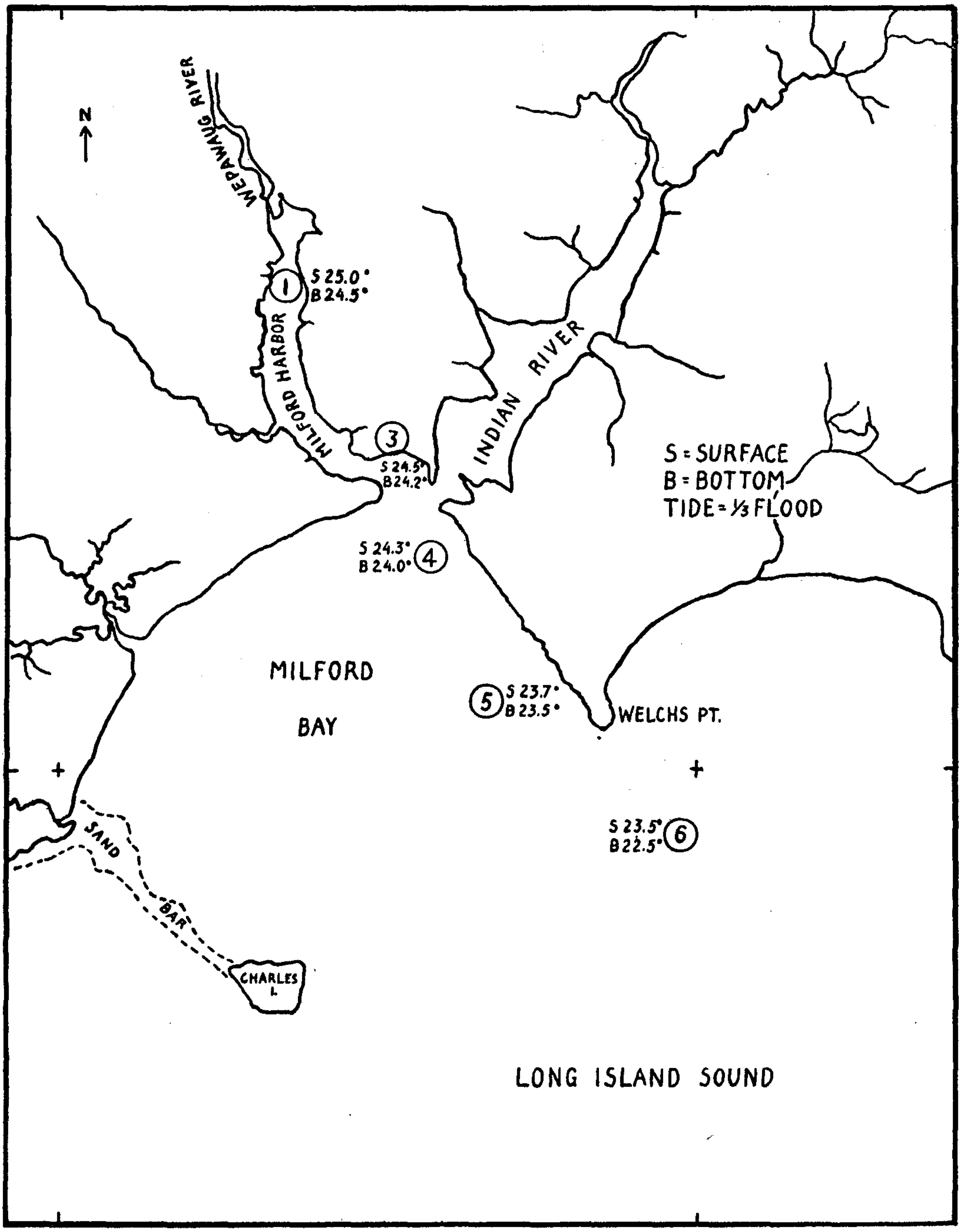

FIGURE 4.—Distribution of surface and bottom temperatures, July 15, 1925

TABLE 3.—*Water temperatures at Station No. 2, 1926, in ° C.*

Date	July				August			
	Extremes		Daily		Extremes		Daily	
	Maximum	Minimum	Mean	Range	Maximum	Minimum	Mean	Range
1	17.5	10.5	13.5	7.0	23.5	19.0	21.5	4.5
2	15.5	11.5	13.2	4.0	24.0	20.0	22.4	4.0
3	17.0	13.0	14.8	4.0	28.5	23.0	26.4	5.5
4	19.0	13.5	15.8	5.5	31.0	21.5	24.4	9.5
5	20.0	14.5	16.8	5.5	27.0	21.5	23.4	5.5
6	18.5	14.5	17.0	4.0	25.0	21.0	24.0	4.0
7	23.0	15.5	18.0	7.5	25.0	22.0	23.4	3.0
8	23.0	16.0	19.2	7.0	25.0	13.5	21.8	11.5
9	25.0	17.0	21.5	8.0	26.0	18.0	21.2	8.0
10	27.0	17.5	22.4	9.5	26.0	19.0	23.2	7.0
11	20.0	12.5	15.2	7.5	26.0	19.5	23.4	6.5
12	19.0	13.0	16.5	6.0	23.5	21.0	22.2	2.5
13	20.0	16.0	17.4	4.0	29.0	22.0	24.4	7.0
14	18.0	14.5	16.0	3.5	27.0	20.5	23.4	6.5
15	16.5	12.0	14.4	4.5	25.5	20.5	23.2	5.0
16	16.5	13.0	14.0	3.5	24.0	22.0	23.2	2.0
17	20.5	15.0	17.4	5.5	23.5	22.0	23.2	1.5
18	20.5	16.0	18.0	4.5	22.0	18.0	20.5	4.0
19	19.5	13.0	15.2	6.5	21.5	18.5	20.4	3.0
20	21.0	15.0	18.2	6.0	23.0	17.0	20.0	6.0
21	25.0	15.0	20.4	10.0	18.0	14.0	16.5	4.0
22	26.0	15.0	19.6	11.0	19.0	16.0	17.6	3.0
23	24.0	15.0	18.4	9.0	23.0	17.0	19.8	6.0
24	23.0	16.0	19.2	7.0	20.5	19.0	19.5	1.5
25	26.0	16.5	18.6	9.5	20.0	19.0	19.2	1.0
26	23.0	16.0	18.8	7.0	22.0	18.0	19.8	4.0
27	23.0	18.0	20.4	5.0	21.5	19.0	20.2	2.5
28	24.0	19.5	21.6	4.5	23.0	19.5	21.2	3.5
29	20.0	19.0	19.5	1.0	25.0	20.0	22.8	5.0
30	23.5	20.5	21.2	3.0	23.0	17.5	20.4	5.5
31	22.0	20.5	20.6	1.5	20.0	16.0	18.0	4.0
Monthly mean	21.7	15.3	17.8	5.9	23.9	19.2	21.6	4.7

The daily range of water temperature varies from 1 to 11.5 degrees and is indicative of the continuous fluctuations that occur in these inshore waters. It also shows very well how little value can be given to occasional water-temperature observations in such localities. The records given in these tables have been plotted in Figure 5 so as to show more clearly the extremes of water temperature for each day together with the daily mean. The maximum, in virtually every instance, corresponds to the water temperature at the time of low water, while the minimum invariably occurs at high water, when the greatest quantity of water has been brought in by the flood tide from the Sound. It is apparent from these graphs that at certain times the daily range of temperature was much greater than the average monthly range, as, for example, on July 6 and 19 and August 20, 1925, and on July 10 and 22 and August 4, 1926, when the daily range of temperature was from 7.5° to 11° C. These periods were found to correspond to the times when there were certain tidal conditions, which are discussed in detail in the paragraph on the effect of tide on temperature.

In order to understand and make clear the causes of the changes in temperature that have been discussed, it is necessary that each important climatological and hydrographical factor be taken up separately with regard to the effect it produces.

As a basis for discussion, the normal climatological data for this region are shown in Figure 6. The monthly means are taken from the records of the United States Weather Bureau station at New Haven, Conn., which is but 9 miles east of Milford.

The water temperature in Long Island Sound and especially its inshore waters are dependent upon the local weather conditions and those in adjacent regions and will follow them quite closely in their general trend.

SOLAR RADIATION

The sun is the primary source from which the water derives its heat. The quantity of heat that the water absorbs is proportional to the intensity of solar radiation, which varies during the months of the year, as shown in Figure 6. Its

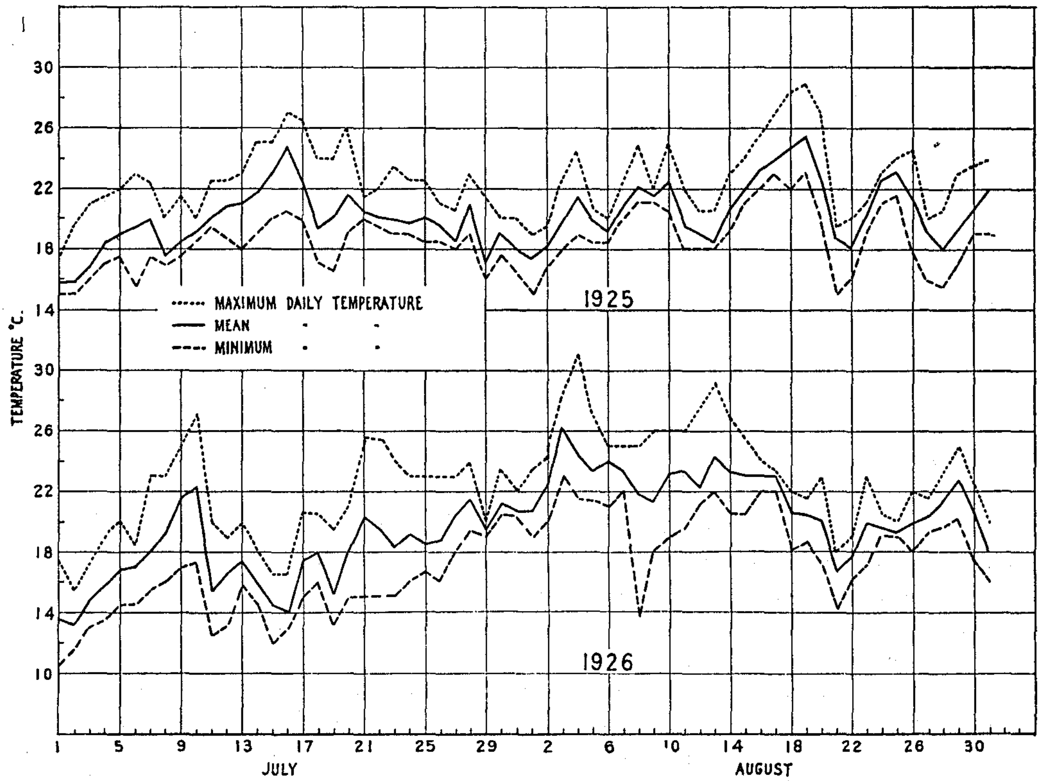

FIGURE 5.—Daily water temperatures, Milford Harbor, 1925 and 1926

intensity is greatest during the latter part of July and is responsible for the maximum air and water temperatures that occur at that time of the year. Although the water is warmed considerably by direct absorption, the greatest effect of sunlight on water temperature is the heating of the air and the land with which the water comes in contact.

Solar radiation has a pronounced effect upon the temperature of the water in Long Island Sound because of its configuration and tidal conditions. As a result of these conditions, the water is kept in constant motion and brought into contact with large land areas or tidal flats, which have a temperature much higher than that of the air because of the absorption of a greater proportion of the sun's heat. The effect of solar radiation on air, land, and water temperature will vary according to the clearness of the day and the number of hours of sunshine that are possible at that time of the year. During July the total number of hours of possible sunshine for this latitude is 458.3, and there is a gradual decrease in the number of hours per

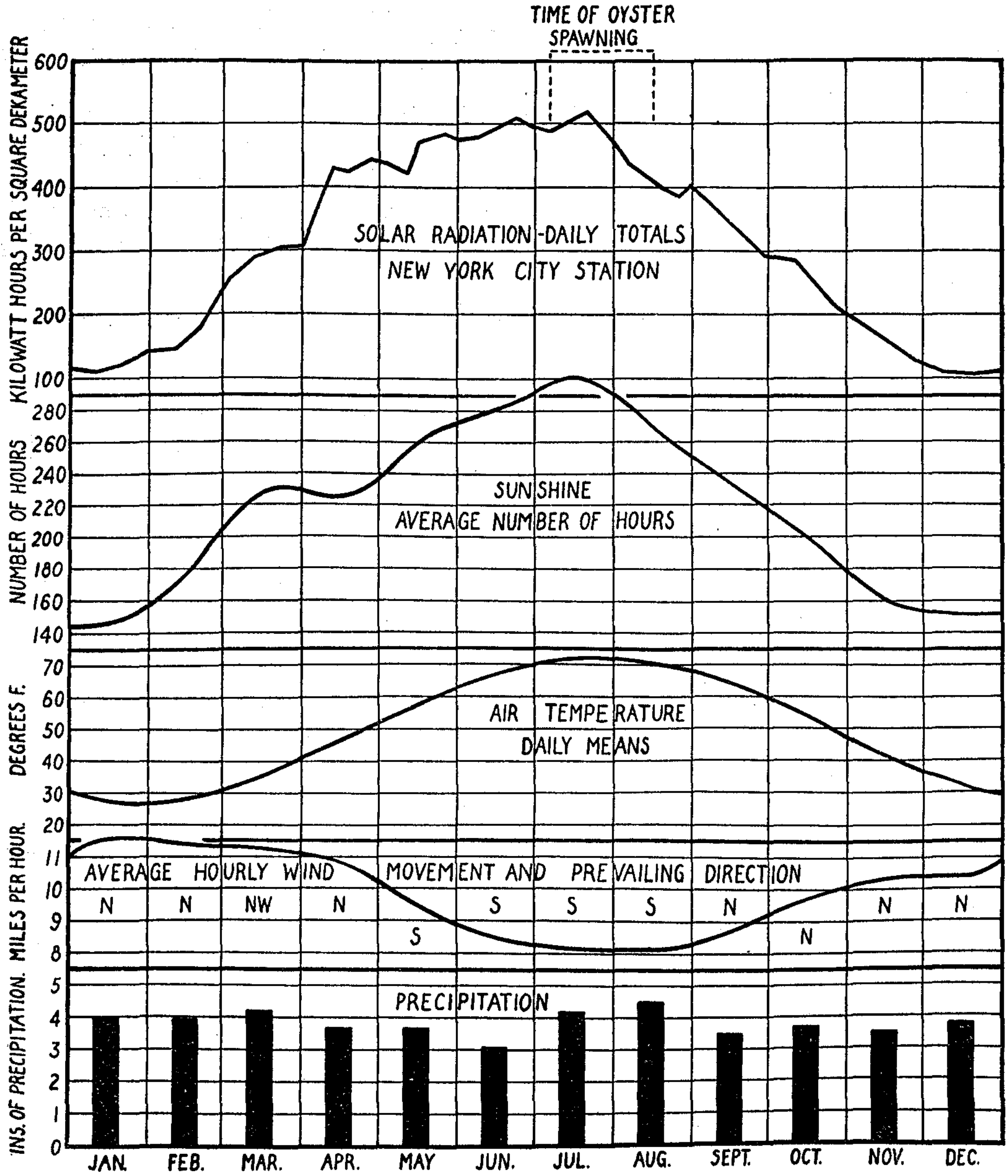

FIGURE 6.—Normal climatology for New Haven, Conn., taken from records of the United States Weather Bureau

day from 15.1 on July 1 to 14.4 on July 30. For the month of August the total number of hours is 426.9, and there is a gradual daily decrease from 14.3 on the 1st to 13.2 on the 30th. In July we normally have sunshine for 302 hours, or 66 per ent of the total possible number for this month, and in August for 265 hours, or 62 per cent.

In July, 1925, there was sunshine for 276 hours and in August for 308 hours, while in 1926 there was sunshine for 320 hours in July and for 256 hours in August. Comparing both years, we find only 8 hours' difference between the two during this 2-month period and, similarly, less than 1° difference in the mean air and water temperatures. When the number of hours of sunshine and its intensity are above or below the normal mean for the month, there is invariably a corresponding departure in air and water temperatures.

The number of hours during which solar heating of the water takes place will be found to vary from 0 to approximately 15 per day, and these variations are the fundamental causes of the daily and hourly fluctuations in water temperature that occur during the summer. A good example of the effect of solar radiation on air and water temperatures and the changes it produces are shown in the following table.

TABLE 4.—*Effect of solar radiation on air and water temperatures, August 1 to 3, 1926*

Date	Hours of sunshine	Daily mean air temperature, ° C.	Water temperature, ° C.			
			Daily mean	At 6 a. m.	At 6 p. m.	Daily increase
Aug. 1	2.3	18.9	21.5	20.5	21.0	0.5
Aug. 2	7.5	23.3	22.4	21.0	23.0	2.0
Aug. 3	14.2	28.3	26.4	23.0	28.5	5.5

On these three days the factors of wind and range of tide were virtually constant, while the chief variable was the number of hours of sunshine per day. On August 1, when there was the least amount of sunshine, the increase in water temperature was exceedingly slight, while on August 3 there was sunshine for 99 per cent of the possible number of hours, which resulted in an increase in water temperature of 5.5° C. during the day.

AIR TEMPERATURE

A close relationship exists between the air and water temperatures in inshore coastal areas and the river waters emptying into them. Although the range of water temperature is considerable, it is much less than the range in air temperature. In the following table, a comparison of the characteristics of the two for the summers of 1925 and 1926 is given.

TABLE 5.—*Comparison of air and water temperatures, monthly data, ° C.*

Monthly data	July, 1925		July, 1926		August, 1925		August, 1926	
	Air	Water	Air	Water	Air	Water	Air	Water
Mean	21.8	19.7	22.0	17.8	21.6	20.8	21.8	21.6
Mean maximum	26.2	22.3	27.0	21.1	26.8	22.9	25.9	23.9
Mean minimum	17.2	17.9	17.0	15.3	16.4	19.0	17.8	19.2
Highest	33.3	27.0	38.3	27.0	32.8	29.0	34.4	31.0
Lowest	12.8	15.0	12.8	10.5	9.4	15.0	12.2	13.5
Greatest daily range	13.3	7.5	16.1	11.0	15.6	7.0	13.3	11.5
Least daily range	3.9	1.5	4.4	1.0	3.3	1.0	3.9	1.0

The relationships between the mean air and water temperatures for July, 1925 and 1926, apparently are contradictory in view of the fact that the water was 1.9° C. lower in 1926, though the air temperature was actually higher than in 1925. However, under the circumstances this is what we would expect because of the difference in the water temperatures on July 1, which were 2.3° C. higher in 1925.

The influence that the air temperature exerts on the temperature of the water is modified to a great extent by wind, precipitation, river discharge, range of tide, and

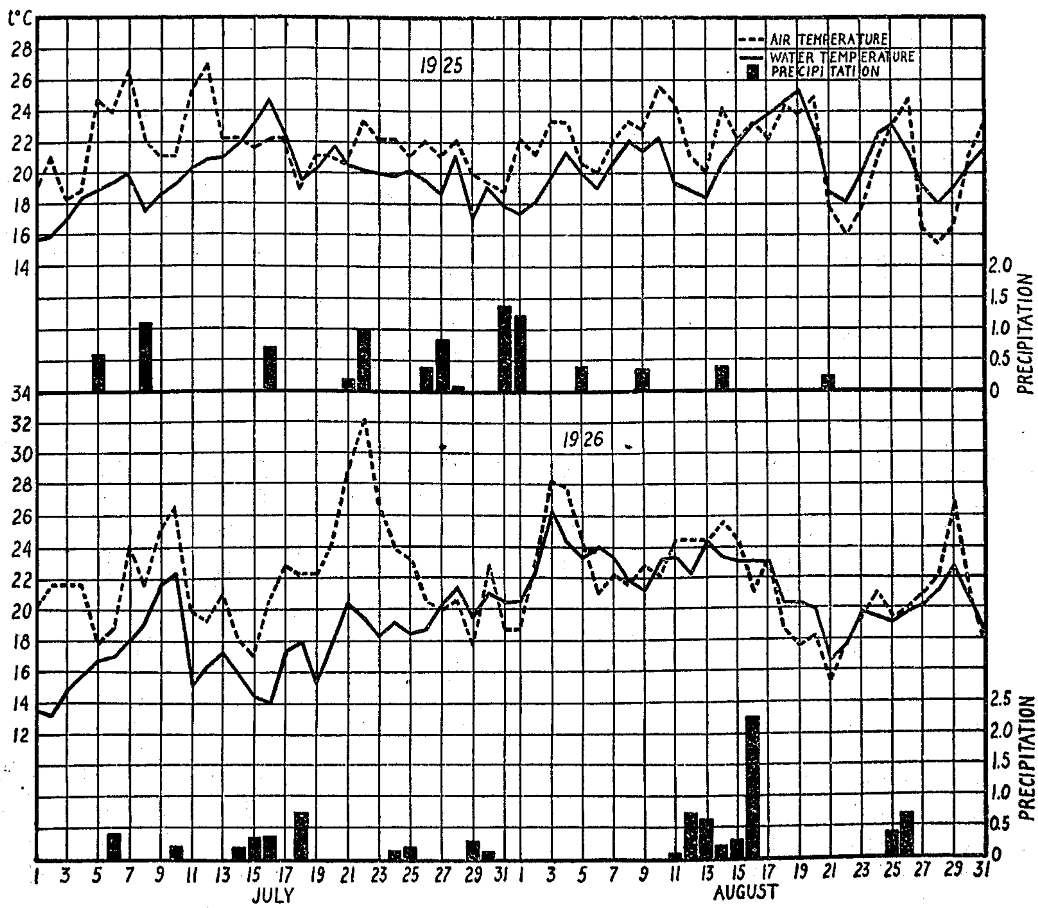

FIGURE 7.—Comparison of mean daily air and water temperatures, together with daily precipitation

the area of tidal flats. The relationship between the air and water temperatures for the summers of 1925 and 1926 is shown clearly in Figure 7. The two curves do not coincide, but, as one would expect, the water curve follows the air curve with a slight lag and less amplitude. A rise in air temperature is followed about 24 hours later by a less prominent rise in water temperature. This is due largely to the fact that the thermal capacity of water is about three thousand times that of the air. Records of the New Haven station of the United States Weather Bureau show that the mean daily air temperature reaches its annual maximum during the period from July 10 to August 5. This is true for the water temperatures, also, as the trend of the two is approximately the same during the annual cycle.

In comparing the monthly mean temperature of the air with that of the water in Milford Harbor, we find that during the summer months the air ranges only from 1 to 2 degrees higher. This relationship can be used as the basis for estimating the approximate water temperatures over a period of six years (from 1922 to 1927) when thermograph records were not available. Obviously, when air temperatures are above normal the water is correspondingly warmer, and when they are below normal the water temperatures are noticeably lower. Thus, analysis of

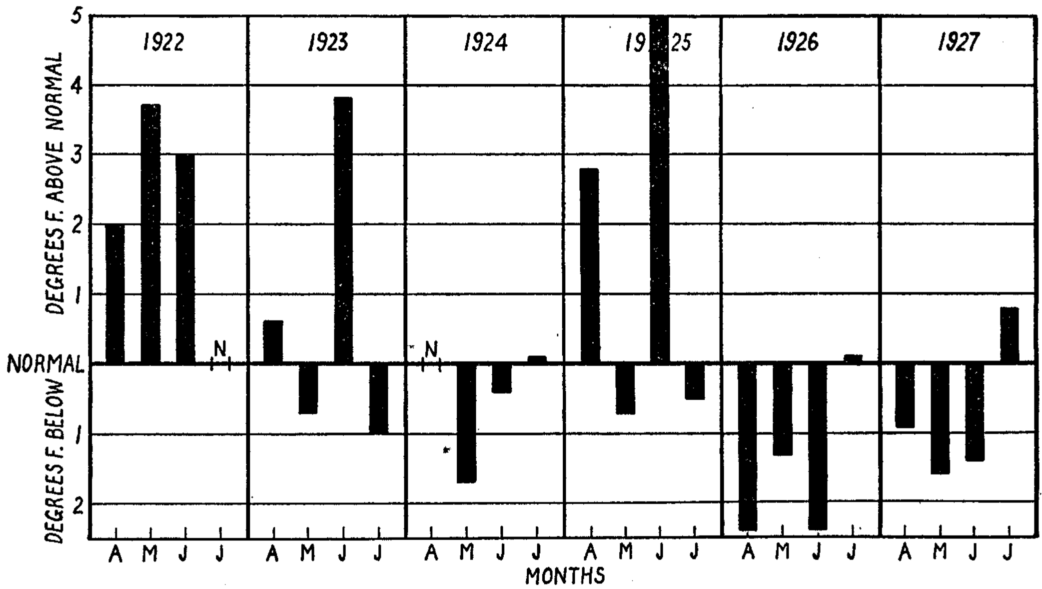

FIGURE 8.—Monthly departure of air temperature from normal, as shown by records of the United States Weather Bureau, New Haven, Conn. The normal mean temperature, in ° F., for April is 46.9; May, 57.8; June, 66.6; and July, 72

the mean monthly air temperatures for any year will indicate the probable water temperatures that occur in small, partially inclosed basins. For this purpose the departure of the air temperature from normal can be used as an index to the prevailing conditions. The monthly departures of air temperature for April, May, June, and July of each year from 1922 to 1927 are presented in Figure 8. In April the water temperature reaches a degree at which the oyster resumes feeding after having been in hibernation since November, and, consequently, we are interested in temperature conditions from this time until spawning occurs in the latter part of July. The monthly differences in air temperatures occurring during this period in each of these years are at once apparent, and when they are summarized for the entire period we find that for three of the years the temperature was above normal and for the other three below. The significance of these departures is discussed later in connection with their effect on spawning and setting.

PRECIPITATION

In rainfall or precipitation we have another important climatological factor that should be considered with air temperature. The quantity of fresh water discharged into the harbors depends largely upon the intensity and amount of precipitation, while its temperature is determined by the temperature of the air and land in this particular drainage basin. The effect of precipitation on harbor-water temperatures depends, therefore, on the quantity and temperature of fresh water discharged into it. When both air temperature and precipitation are above normal, as they were in 1922 and 1925, their combined influence on the physical condition of the

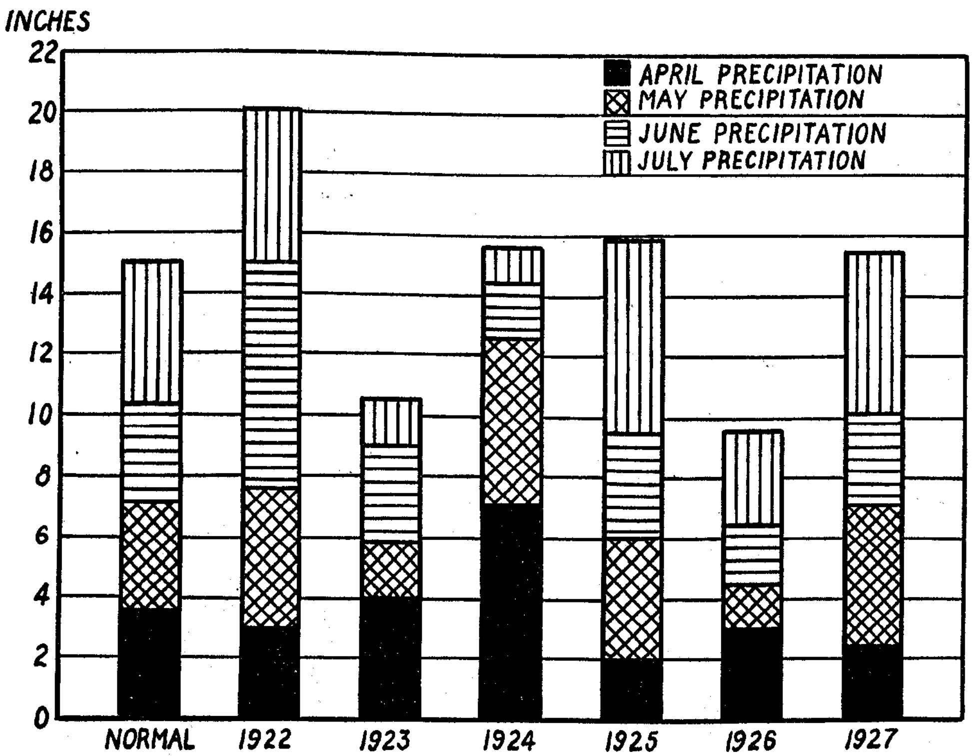

FIGURE 9.—Total precipitation for the period April 1 to August 1

water in the harbor is considerable, as there is not only an increase in water temperature but also a decided change in the chemical composition of the water. The daily precipitation, in inches, for July and August, 1925 and 1926, is presented in Figure 6, together with the water temperatures. In Figure 9 the normal and monthly amounts of the total precipitation for the period April 1 to August 1 is shown for the six years and clearly demonstrates the variations in rainfall that have occurred each spring and summer. According to Hoyt and Grover (1916), in this region approximately 40 per cent of the rainfall reaches the streams as run-off during these months, and its importance can hardly be overlooked in view of the fact that Long Island Sound receives the drainage of virtually all of the State of Connecticut and a large portion of Massachusetts, Vermont, and New Hampshire. In the chapter on river discharge the monthly variations in precipitation are discussed in relation to their effect on the quantity of fresh water emptied into Long Island Sound.

WIND

Another climatological factor that should be mentioned briefly with regard to its effect on water temperatures is wind. The nearest Weather Bureau station from which detailed wind records could be obtained was at Sandy Hook, N. J.

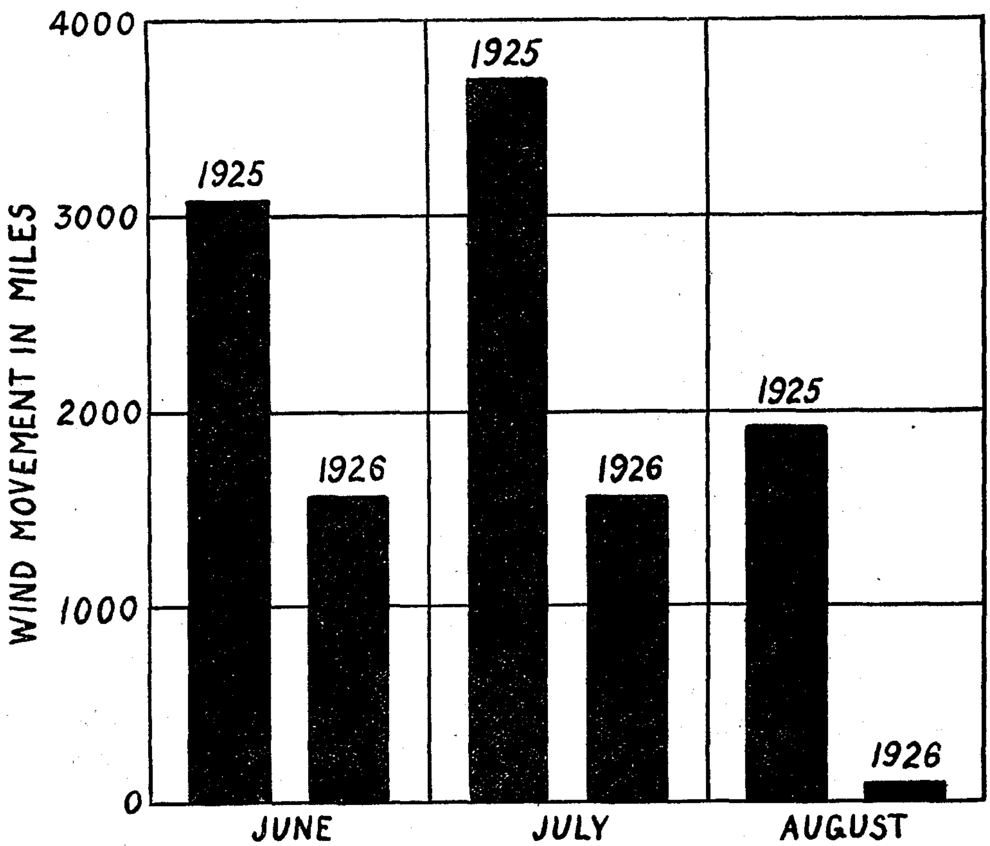

FIGURE 10.—Excess of south component wind movement over north for 1925 and 1926

Taking the two years 1925 and 1926, we find a marked difference in the total monthly wind movements and its direction for the summer months—June, July, and August. For these months the movement of the south wind is invariably greater than the movement of the wind from the north, and the prevailing direction is from the south. In comparing the movement of the south component winds (southeast, south, and southwest) with the north component winds (northwest, north, and northeast), we find a noticeable variation in the number of miles excess of south winds over north winds. As shown by Figure 10, in 1925 the wind movement from the south was 1,487 miles greater than that in 1926 for June, 2,113 miles for July, and 1,848 for August. In other words, for this period the resultant wind movement from the south in 1925 was 5,448 miles greater than it was in 1926. The effect of wind on air and water temperatures depends largely on the original source of the winds, which, in the case of the south component winds, for this region is both land and marine. The southwest winds come from the adjacent Atlantic Coast States lying in that direction, while the south and southeast winds come from over the Gulf Stream.

The wind has great effect on water temperatures in this region because of the exposure of extensive tidal flats, where rapid changes in temperature were found to occur with strong north or south winds. A good example of the effect of a north wind was found on August 8 and 9, 1926, when the temperature dropped from 25° C. at low water at 6 p. m. to 13.5° C. at low water 12 hours later. During this time, the most sudden drops in temperature occurred on the 9th from 4.30 a. m. to 5.15 a. m., when the water cooled from 20° C. to 13.5° C., a decrease of 6.5° in 45 minutes. Although the opposite effect is produced by the south wind, the increase in temperature is not as great because of a certain amount of cooling by evaporation. The wind is an important factor in changing inshore water temperatures, especially in regions where the tidal movement and area of flats is considerable, because the rate of exchange of heat between the air and water depends largely on the area of the surfaces that are brought into contact and the extent of circulation of each medium.

INFLUENCE OF TIDE ON WATER TEMPERATURE

The tide is an important hydrographic factor indirectly affecting the temperature of inshore waters. As a result of the tide, the water undergoes considerable vertical and horizontal movement, thereby coming into contact with the tidal flats, which greatly increases the effect of climatological conditions on its temperature.

In Milford Harbor the mean range of tide is 6.6 feet and the spring range 7.7 feet. The water temperature showed marked variations according to the range and stage of tide and the time of high water in relation to the time of day. Besides solar radiation and air temperature, the magnitude of the hourly and daily variations in temperature was found to depend also upon the range of tide.

The principal purpose in studying the tides was to determine their influence on the development of the maximum temperatures that affect many physiological activities of marine organisms. In comparing 1925 and 1926 water temperatures, it has been found that during the periods of full-moon spring tides there occurred a definite upward trend in the daily mean water temperature.

During the spring and early summer, the ocean water that is brought into Long Island Sound with the tides has a low temperature, while that from the rivers and shallow tidal flats is considerably warmer. In the fall conditions are reversed, the ocean and Sound waters persisting as a warm influence, while those from the land rapidly become colder. The quantity of ocean water coming into the Sound varies from day to day in accordance with regular changes that occur in the range of tide. With spring tides, when the range is greater than the average, we have the maximum inflow of cool ocean water; and with neap tides, the minimum, as at this time the range is less than the average.

In comparing conditions that exist at different tides, we find that during the period of the full-moon spring tides, in July and August, the hourly water-temperature fluctuations are greatest, and the daily average shows a steady increase. We can define the full-moon tidal period as the interval between the first increase in tidal range following first quarter of the moon to that which follows the third quarter of the moon. The length of this period is approximately 15 days, half of which occurs before the time of full moon and the other half after full moon. During the first half of the full-moon tidal period, the tide in Milford Harbor gradually increases in range from approximately 6 feet to 8.5 feet, while during the second half it gradually decreases from day to day until the range is again approximately 6 feet.

The area of tidal flats that are flooded at the time of high water or exposed at low water is smallest at the beginning and end of this period and largest at the middle, when the range of tide is greatest. Similarly, the effect of solar radiation and air temperature on temperature of the water is greatest when the range of tide is highest, because of the greater surface that is exposed.

The rate of increase in the daily water temperature and the maximum degree attained during the full-moon tidal periods in July, 1925 and 1926, are shown graphically in Figure 11. During this period in 1925, the water temperature increased from 15.8° C. at the beginning to 24.8° C. at the end, a rise of 9° in 15 days. Under virtually the same conditions in 1926, the water temperature increased from 18.2° C. to 26.4°, a rise of 8.2° in the same period of time. The similarity of the changes in the daily temperature as recorded by the thermograph at the beginning and end of this period in 1925 and 1926 is also shown in Figure 11. The maximum temperature reached by the water during the full-moon tidal periods depends upon three general conditions, namely, (1) the temperature of the inshore water at the beginning of full-moon tides, (2) the temperature of the ocean water brought in by the tides, and (3) weather conditions during this period. The first two conditions can be determined by direct observations and will vary from year to year in accordance with weather conditions in the preceding spring months. The temperature of the ocean at the mouth of the Sound attains its maximum, which is approximately 18.5° C., from about the 15th of July to the 15th of August. There are, however, noticeable annual differences, of which the 1925 and 1926 records, shown in Figure 12, are good examples. When the ocean temperature has attained 18° or 20° C., its cooling effect on the waters of Long Island Sound during spring tides is not very great and is more than counteracted by the flooding and warming of the water on a much greater area of tidal flats. The third factor, weather conditions, can not be predicted definitely, but an analysis of the meteorological data for many years, as presented in Figure 5, shows that during this period one should expect maximum intensity of solar radiation, maximum number of hours of sunshine, and the maximum air temperatures for the entire year. The influence of intense solar radiation and high air temperatures combined with greatly increased tidal range is responsible for the heating of the water to a temperature of 20° C. and above during this period. Though the water in the Sound does not warm as rapidly nor reach as high a temperature as that in the harbors, it follows closely the trend of the inshore-water temperatures.

In studying the hourly fluctuations in water temperature, we can readily see the actual changes that occur with spring and neap tides and at different stages of the tide, examples of which are given in Figure 13, for the periods July 24 to 26, 1926, and August 2 to 4, 1926. The greatest hourly fluctuations occur with spring tides and the least at the time of neap tides. The lowest water temperatures in the harbor were found to occur at the time of high water and the highest at low water, the difference sometimes being as great as 10 or 12 degrees.

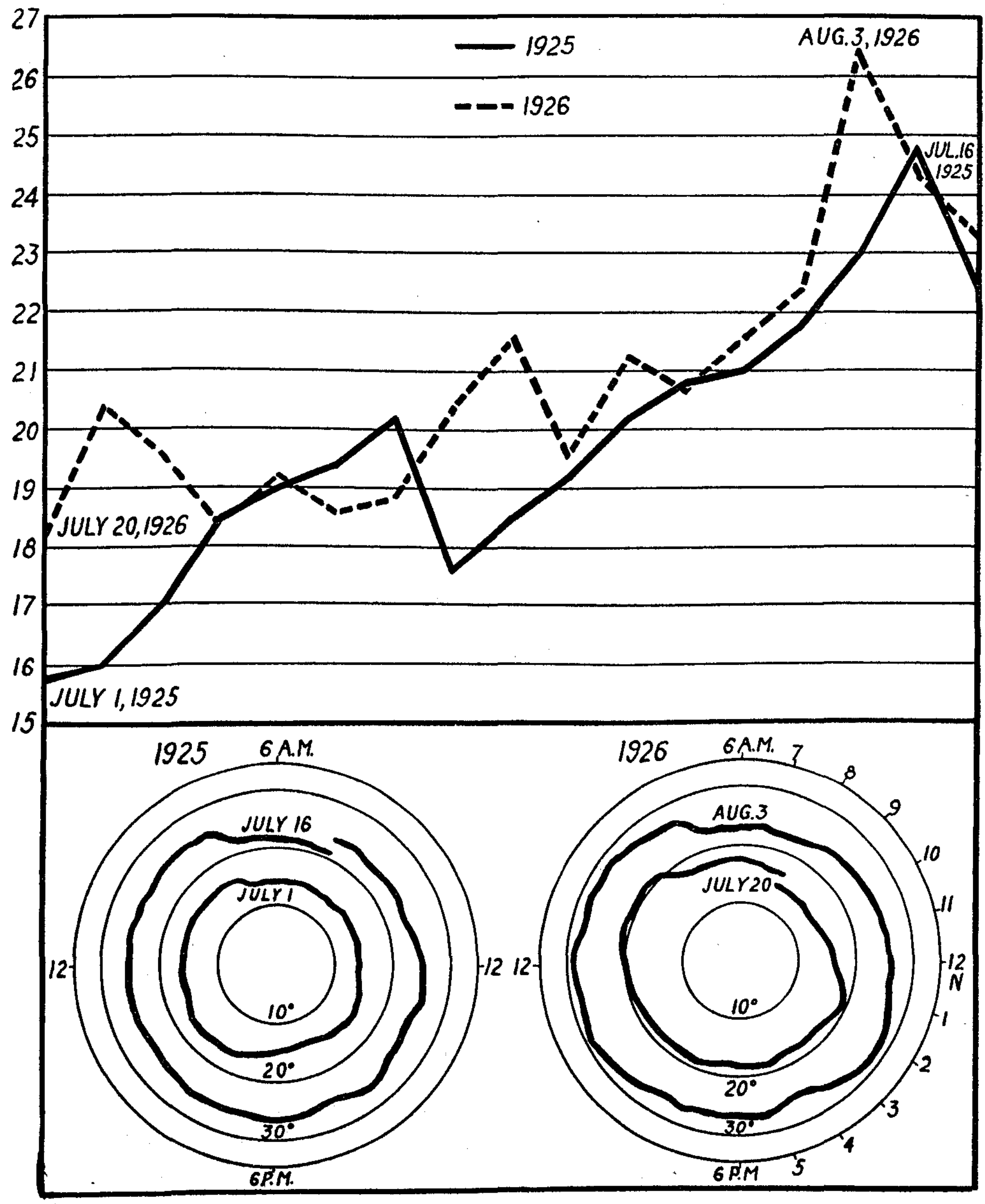

FIGURE 11.—Mean daily water temperature during "full-moon tidal period" in July, 1925, and July, 1926. Copies of thermograph records show the change in the daily temperature from the beginning to the end of this period

The influence of the tide on water temperature may be summarized as follows:

1. The vertical and horizontal movement of the water, as a result of the tide, increases the area of water surface that is brought into contact with the air and land.

2. The magnitude of this movement varies with the range of tide, and both are greatest when the moon is full and in perigee.

3. Since the temperatures of the air and land are highest in July and August, their effect on water temperature will be greatest during the periods of maximum range of tide.

4. Taking into consideration meteorological conditions, the daily and hourly temperature fluctuations can be correlated closely with changes in the stage and range of tide.

TIDE AND CURRENT

In discussing tidal phenomena, the term "tide" is used to designate the vertical movement of the water and "tidal current" to designate the horizontal movement.[1] In the various bays and estuaries along the coast the tidal movement is determined

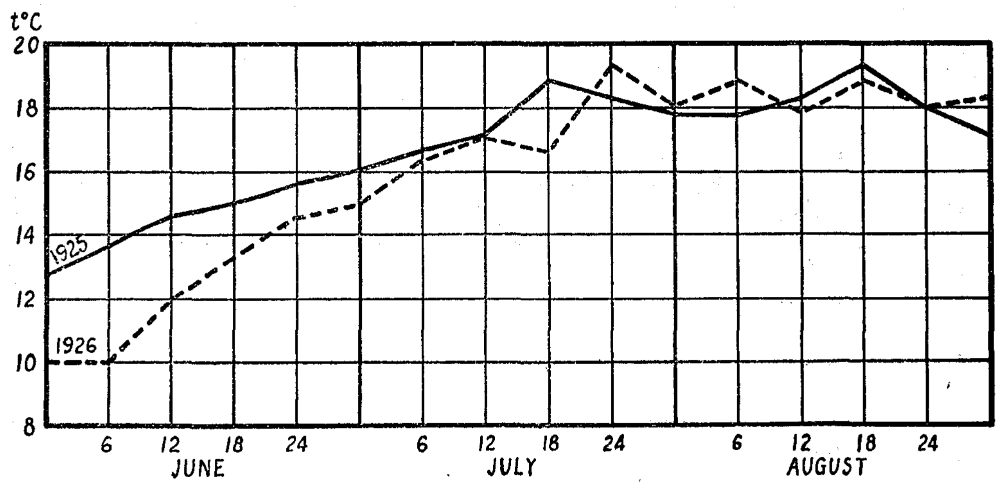

FIGURE 12.—Comparison of the water temperature at the mouth of Long Island Sound in 1925 and 1926

largely by the type of ocean tide that enters them and is modified by the configuration and hydrographic features of the coast in each locality. On the Atlantic coast of the United States the ocean tide is of the semidiurnal type, the chief characteristics of which are that (1) two high and two low waters occur during each tidal day, and there is but little difference between morning and afternoon tides; (2) the rise and fall of the tide varies from day to day according to the position and phase of the moon; (3) spring tides follow full and new moon by one day and are 20 per cent greater than the average, while neap tides follow first or third quarters of the moon by one day and are 20 per cent less than the average; and (4) the duration of rise and the duration of fall of tide are equal, each being about 6 hours and 12 minutes. These are also the general characteristics of the tides in Long Island Sound and Milford Harbor. As the ocean tide enters a partially inclosed basin along the coast, it produces considerable variation in the physical conditions existing there, such as salinity, temperature, H-ion concentration, etc. The hydrography of the region and the range of tide determine largely the extent of variation that is produced. From

[1] In this discussion of tide, statements frequently are taken from "The Tide," by H. A. Marmer, 1926.

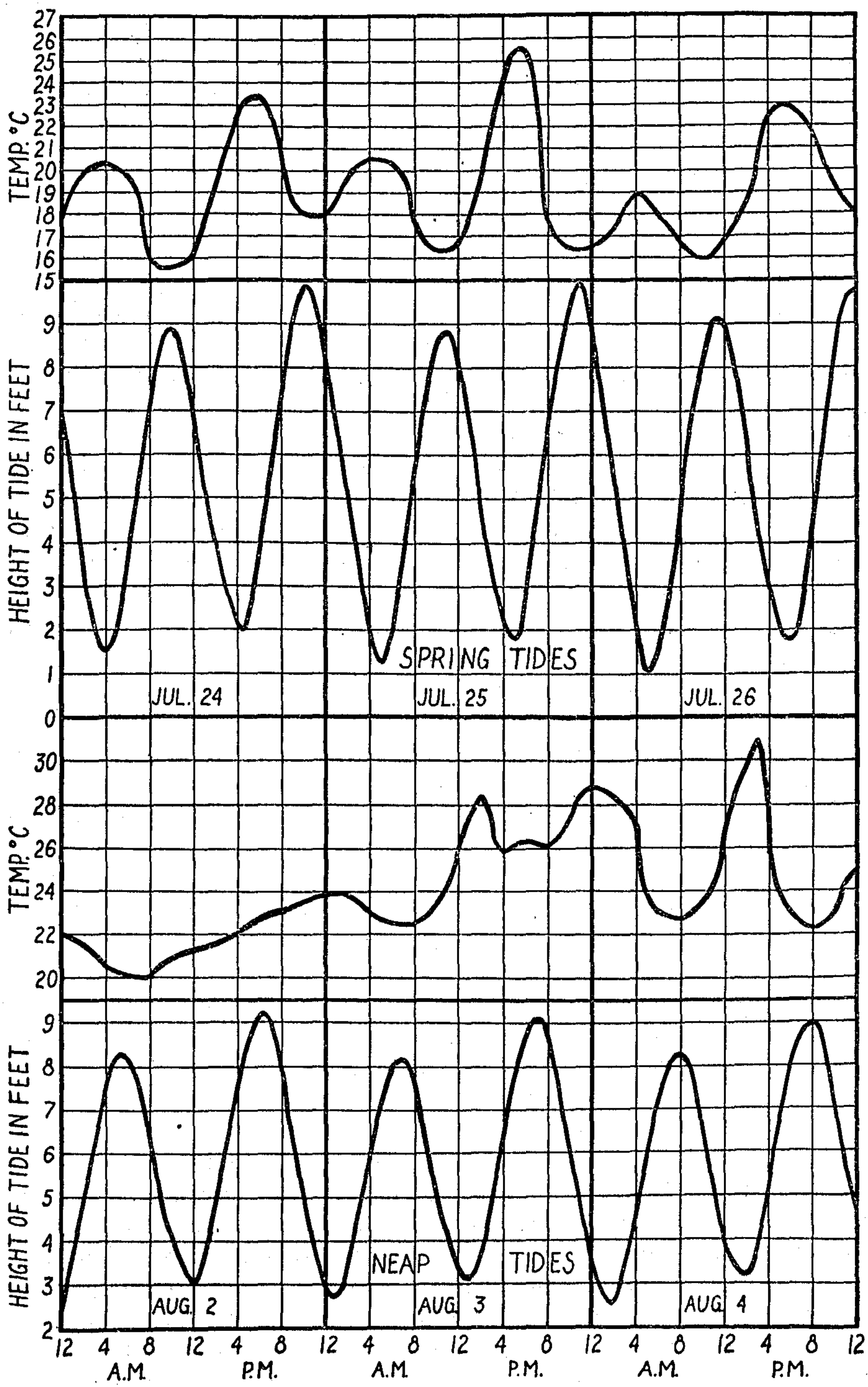

FIGURE 13.—Hourly fluctuations in water temperature during spring tides and neap tides

a biological standpoint both intimately related features of the tidal movement—the rise and fall of the water and the horizontal movement or tidal current—are of considerable importance.

According to Marmer (1925), in most bays and rivers of the Atlantic coast the tide enters as a progressive wave, the characteristics of which are that the strength of the tidal current is greatest at the times of high and low water while the slack of the current comes midway between the times of high and low water. However, in Long Island Sound and its inshore waters we find a different kind of movement, which is of the stationary-wave type. With this type of wave movement the strength of the current comes midway between high and low water, while the slack of the current comes near the times of high and low water. This difference is illustrated by Figure 14, in which the tide and current curves are plotted for Milford Harbor entrance, where the movement is of the stationary-wave type, and for New York Harbor (Marmer, 1925), as determined by the Coast and Geodetic Survey, where we have progressive wave movement.

In each locality the tidal currents vary in strength from day to day in accordance with the changes in the range of tide. The strongest currents come with the spring tides of full and new moon, and the weakest currents with the neap tides of the moon's first and third quarters. During the spring tides the flood current in Milford Harbor attains a maximum velocity of 1.1 feet per second, and the ebb current, 1.5 feet per second. With neap tides considerably less water passes in and out of the harbor, and the velocity of the flood current at strength is 0.8 per second and the ebb current 1.3 feet per second. The tidal current in Milford Harbor is of the rectilinear or reversing type—that is, the flood current runs in for a period of approximately 5 hours and 30 minutes and the ebb current runs out for a period of 6 hours.

In studying the tidal current and its possible effect on the occurrence and distribution of the oyster larvæ a complete understanding of the direction as well as the velocity of the current at each stage of the tide is necessary. For this purpose the Eckman current meter and several sets of drift bottles were used. The direction of flow during flood and ebb is shown in Figure 15 for Milford and vicinity. During a complete tidal cycle the distance traveled by an object floating in the water or by a buoyant microorganism is equal to the product of time multiplied by the average velocity during this interval. For a normal flood or ebb period of 6.2 hours, the approximate distance a tidal current with a velocity, at strength, of 1 knot will carry a floating object is 3.95 nautical miles or 24,000 feet. (Marmer, 1925.)

As a result of river discharge the ebb current has a greater velocity and duration than the flood, and currents of such strength as those at the entrance of Milford Harbor would transport a floating object approximately 21,100 feet during the ebb flow and return it but 15,600 feet during the flood. The currents inside and outside of the harbor are not as strong as those at the narrow entrance, so, in order to determine the actual direction and drift of the currents, several observations were made with floats. In each case two pairs of floats were used and were released at Station 2, in the harbor, and their course charted for several hours. When the floats were released, at the beginning of ebb tide, they followed the channel to Station 5 and then swung east, passing the red buoy near Station 6 in approximately 2½ hours, and finally came to a stop about 1,000 yards offshore at Pond Point. The distance the floats were transported by the ebb current was over 15,000 feet in a period of 6 hours. With the change of current from ebb to flood the floats were carried west nearly to Welchs Point, and then swung in toward shore and into the rotating current in this little bay. When the floats were released on the last of ebb tide from Station 2, they

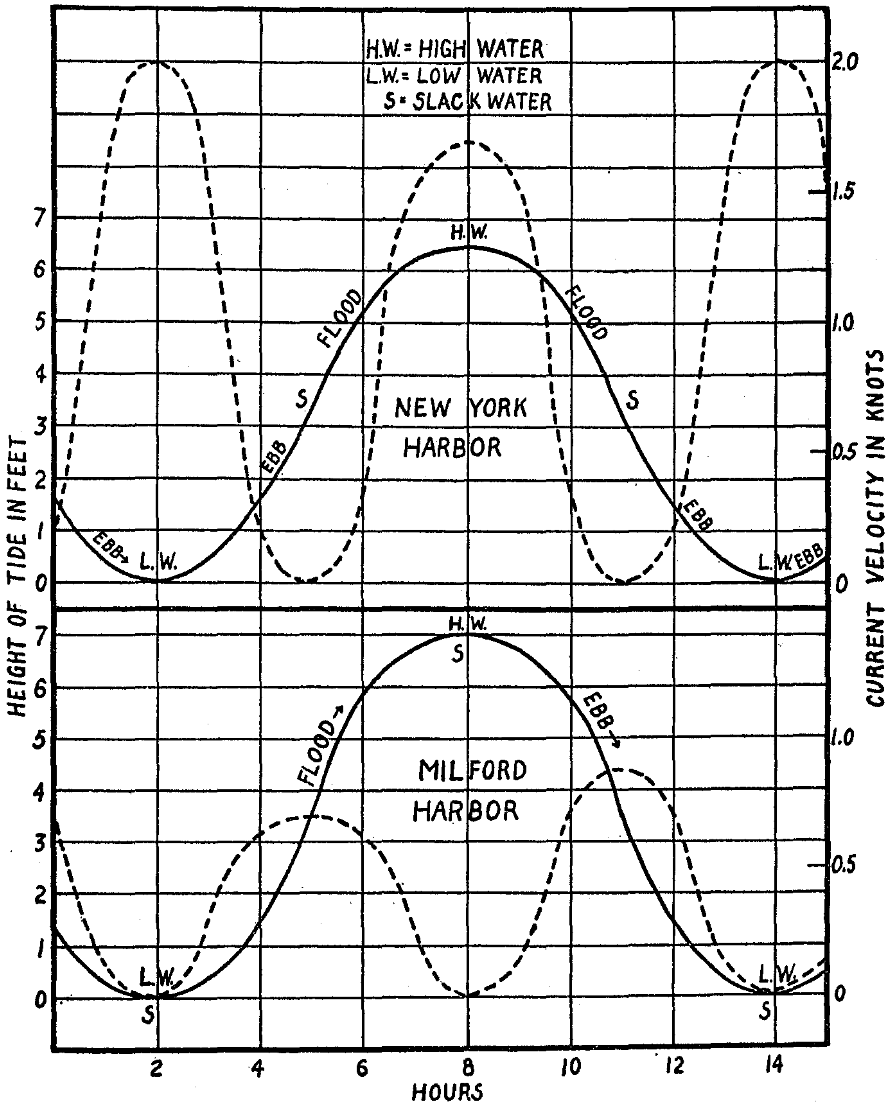

FIGURE 14.—Comparison of tide and current relationships in Milford and New York Harbors

were carried out of the harbor as far as Station 5, and there met the first part of flood tide in the Sound, which carried them to the west in a large circle, finally washing them ashore about 1 mile from the harbor entrance.

From these observations it is apparent that any object floating freely in the water will be carried out of the harbor by the tidal currents in the first day and never

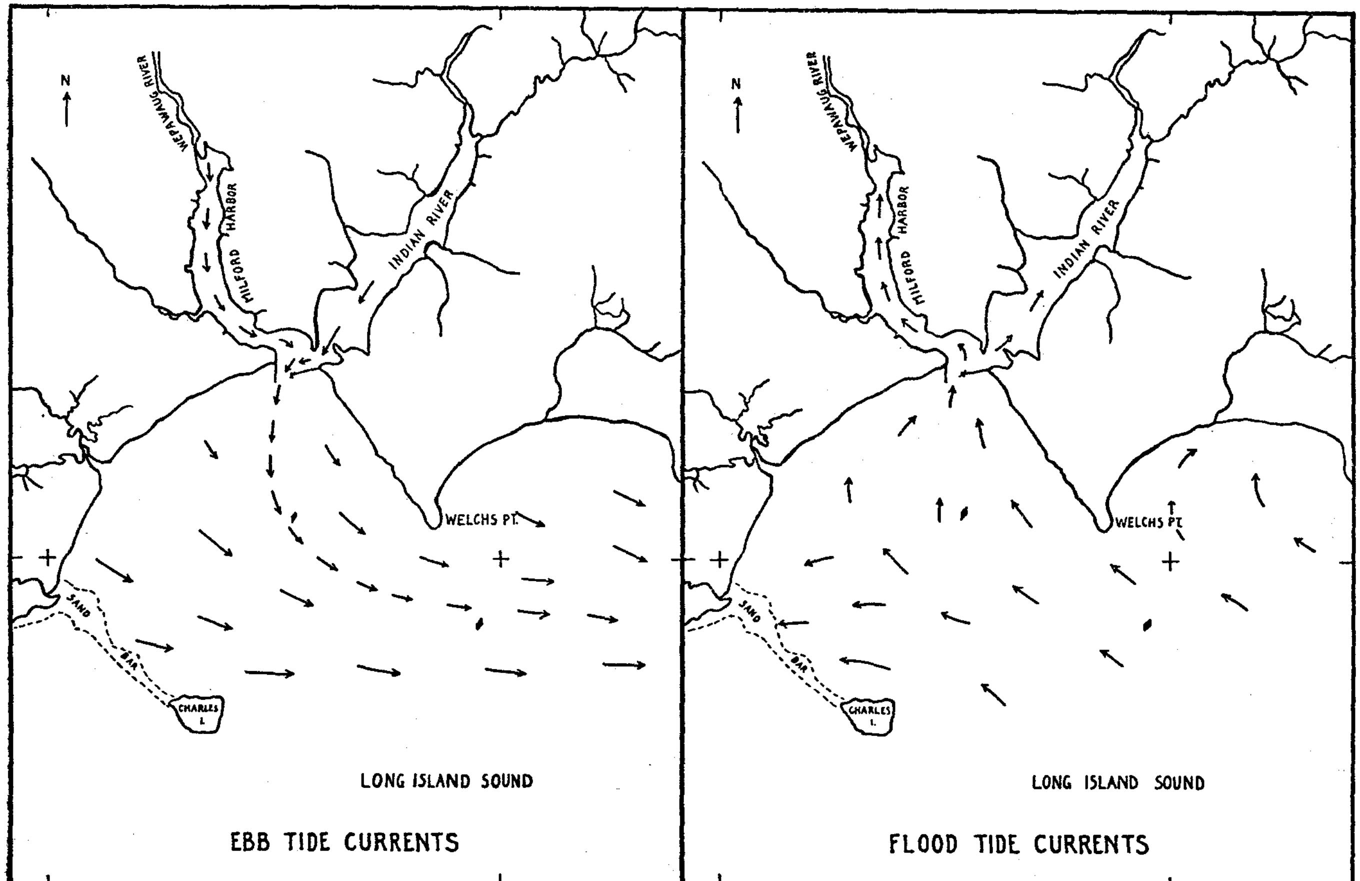

FIGURE 15.—Direction of flood and ebb tide currents in Milford Harbor and vicinity

will be transported back to it. This consideration has a bearing on the distribution and occurrence of oyster larvæ in the harbor and Sound, which will be discussed later.

Briefly summarized, the chief characteristics of the tides and currents in Milford Harbor are as follows:

1. The mean range of tide is 6.6 feet.
2. With spring tides the maximum range recorded during the summer was 9 feet, while with neap tides the minimum range was 4.2 feet.
3. The tide is of the semidiurnal type and possesses the general characteristics of the Atlantic Ocean tide, as described previously.
4. The tidal currents are of the rectilinear or reversing type.
5. The duration of the flood current is approximately 5½ hours, and of the ebb current 6 hours.
6. The currents attain their greatest velocity when the tide is halfway between high and low water mark.
7. The velocity of the ebb current is approximately one-third greater than the velocity of the flood current.
8. The period of slack water, or zero velocity, occurs at the times of high and low water. With neap tides, slack water lasts for an interval of about 1 hour, and with spring tides only 20 minutes.

TIDES AND CURRENTS IN LONG ISLAND SOUND

Studies of the tides and currents were not confined entirely to Milford Harbor but were carried on in Long Island Sound also, as this is the largest and most important seed-oyster producing region in the north. Here the tidal currents are rather complex, and, in order to study them, several experiments were made with drift bottles in addition to the current-meter observations.

The current-meter observations consisted of determinations of the velocity and direction of the current at various stages of the tide and were made at two stations off Milford. Observations made during ebb tide showed that the predominant direction of the current during this period was E. 20° S., and that the maximum velocity was 0.9 foot per second. During the flood tide the current does not run in one general direction but swings to the right through an arc of 140° from low water to high water. The direction and velocity at four stages of the flood tide are as follows:

TABLE 6

Stage	Predominating direction	Velocity (knots)
First-quarter flood	W. 20° N.	0.25
Second-quarter flood	W. 40° N.	.85
Third-quarter flood	N. 40° E.	1.15
Fourth-quarter flood	N. 70° E.	.30

The veering of the current to the right during this flood cycle can be attributed to two chief causes: (1) The rotation of the earth, in consequence of which all moving bodies are impressed with a force that, in the Northern Hemisphere, deflects them to the right of the direction in which they are moving. The water on the flood tide would be deflected to the Connecticut shore and that on the ebb to the Long Island shore. Evidence of such deflection is found in the difference in range of tide on the two shores, high water being higher and low water lower on the Connecticut shore than on the Long Island shore. (2) The configuration and hydrographic features of the Sound. The convergence of the shore lines between Stratford Point and Oldfield Point and between Norwalk and Eatons Point confines the tidal wave as it advances up the Sound, forcing the water to expand into the bays and estuaries. Virtually all such areas are on the Connecticut shore, and the large quantity of water that passes into them results in changing the course of the flood tide during the latter period of rise. A similar rotation of the flood current, but in an anticlockwise direction, has been reported for the Long Island shore, between Herods Point and Ortons Point, by people long familiar with this region.

Summarizing the current-meter observations, it can be stated that though the tidal currents in Long Island Sound are chiefly of the rectilinear or reversing type, there is a clockwise rotation along the Connecticut shore during the last half of the flood tide.

This rotary movement, combined with the greater velocity and duration of the ebb current, results in a dominant drift over the Connecticut oyster grounds in approximately an ENE. direction. The observations indicated that during a tidal cycle a floating object released at the beginning of ebb tide will travel toward the entrance of the Sound with the ebb current, and on the change to flood will retrace its path for about 3 hours and then swing in a large arc to the right toward the shore, finally arriving at high water at a point about 2 miles ENE. from where it was released. The actual course traveled by the floating object will vary somewhat according to the range of tide, river discharge, and point of release.

DRIFT-BOTTLE EXPERIMENTS

On September 18 to 21, 1926, 500 drift bottles with drags attached were released in groups at various places off Stratford Point and Milford. In Table 7 the general record of release and recovery is given, and in Table 8 is shown the percentage recovered during the first month in each of the three major regions—Connecticut, entrance of the Sound, and Long Island.

TABLE 7.—*Drift-bottle record*

Experiment	Group	Locality	Tide	Number released	Total number recovered	Recoveries, according to months						Per cent recovered
						1	2	3	4	5	6 to 10	
A	1	Stratford Point to Stratford Shoal.	High water	100	38	24	5	3	3	1	2	38
	2	do	Low water	100	60	41	9	3	5	1	1	60
B	3	Housatonic River	¼ ebb	50	24	16	4	1	1	0	2	48
	4	do	¾ ebb	50	30	24	5	1	0	0	0	60
C	5	Charles Island	¼ ebb	25	18	15	3	0	0	0	0	72
	6	do	½ flood	50	36	24	5	1	1	3	2	72
	7	Milford Harbor	½ ebb	25	17	11	0	1	0	0	5	68
	8	Welchs Point	½ flood	100	67	48	7	0	3	5	4	67
Total				500	290	203	38	10	13	10	16	58

TABLE 8.—*Per cent of drift bottles recovered during the first month, according to location*

Experiment	Group	Connecticut	Entrance of Sound	Long Island
A	1	50	33	17
	2	70	3	27
B	3	88	6	6
	4	67	0	33
C	5	67	0	33
	6	83	0	17
	7	99	0	1
	8	90	1	9
Total		76.7	5.3	18

In a period of 10 months, 290, or 58 per cent, of the bottles were recovered. Taking the groups as a whole, we find that 70 per cent of the recovered bottles were collected during the first month, 13 per cent in the second month, and the remainder, about equally divided over the next eight months. The records of the bottles recovered during the first month are of greatest significance, and, in analyzing them the factors of time, distance, and points of release and recovery have been considered carefully. In discussing the results it is necessary that each experiment be taken up separately because of the different conditions in each locality.

Experiment A.—(See figs. 16 and 17.) This experiment was planned so as to cover the most valuable oyster-seed producing region in Connecticut. The drift bottles were released in groups of 10 from the northeast corner of oyster lot No. 771, at Stratford Point, out to Stratford Shoal Lighthouse, a distance of approximately 6 miles. The bottles in Group 1, which were released at the time of high water, were transported first by the ebb current in the Sound, while those released in Group 2 were carried first by the flood current. The recoveries in Group 1 were all made to the eastward, and in no instance were bottles recovered west of the line of release. In Group 2 the effect of the flood current is shown by the recovery of 16 bottles to the west of the line of release, though as a whole the bottles of this group were carried eastward also. The fact that 60 per cent of Group 2 were recovered and only 38 per cent of Group 1 is due chiefly to two factors—(1) the shoreward movement of the flood tide, which deposited a greater number on the Connecticut coast, and (2) the discharge of the Housatonic River, which caught the bottles as they were moving eastward and forced them over to the Long Island shore. Further influence of these two factors is shown in the difference in distribution of the bottles by the currents and the percentage recovered in each region. If we analyze the results over shorter periods of time, as, for example, by weeks, we find that during the first two weeks the majority were found on the Connecticut shore, the third week at the entrance of the Sound, and during the fourth week on the north shore of Long Island. Only 1 of the bottles of Group 2 succeeded in getting out of the Sound, while 5 of Group 1 were recovered outside, 3 of which went to the Green Hill Coast Guard Station in Rhode Island, a distance of 80 miles from the point of release, in approximately 14 days.

In Group 2, the farthest distance covered by a bottle drifting to the east was 50 miles and to the west, 14 miles. In this experiment the general distribution of the drift bottles in relation to time, tide, and point of recovery also indicates a clockwise rotary circulation of the water in the Sound.

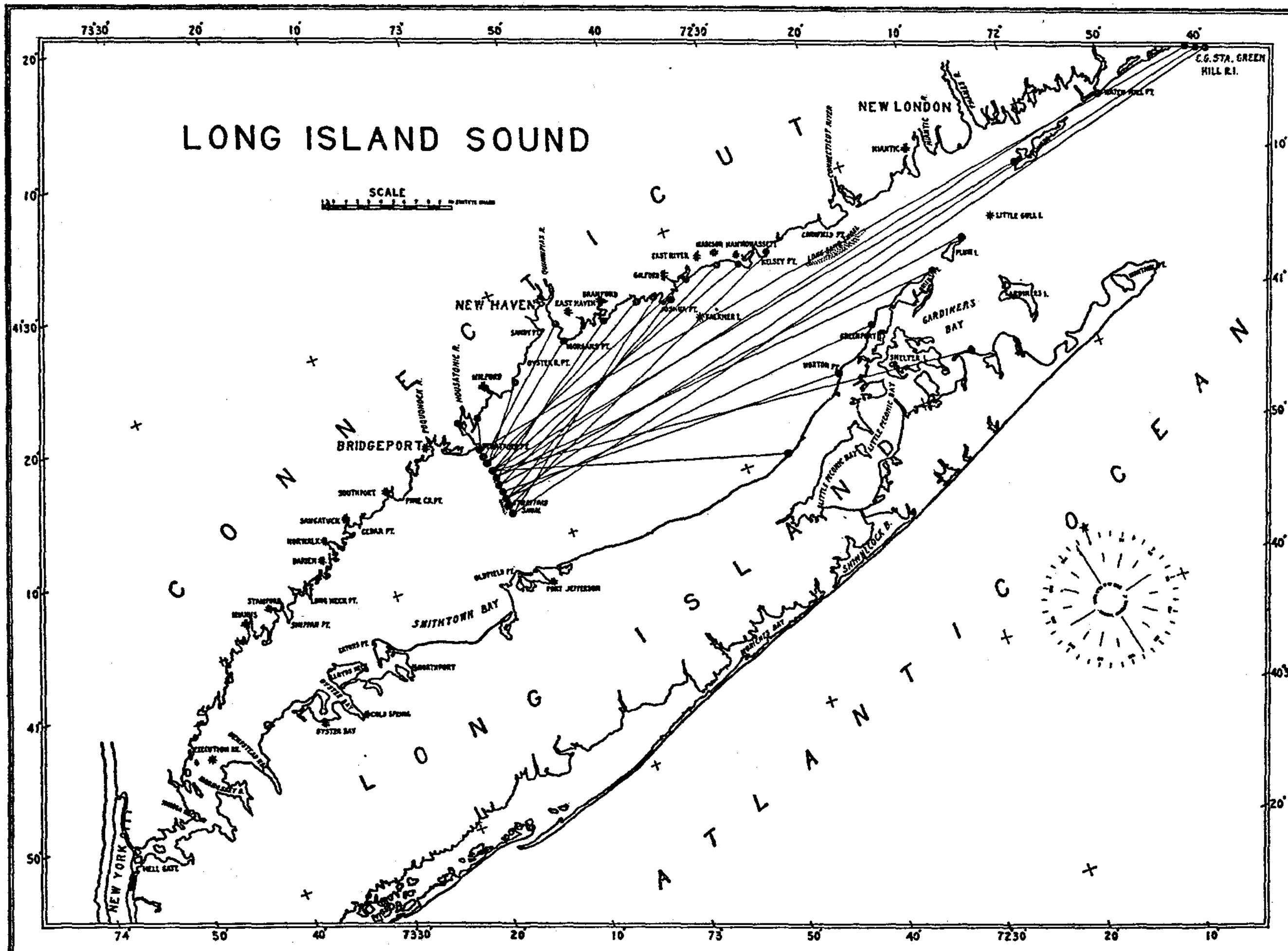

FIGURE 16.—Experiment A, Group 1. Place of release and recovery of bottles put out at high water

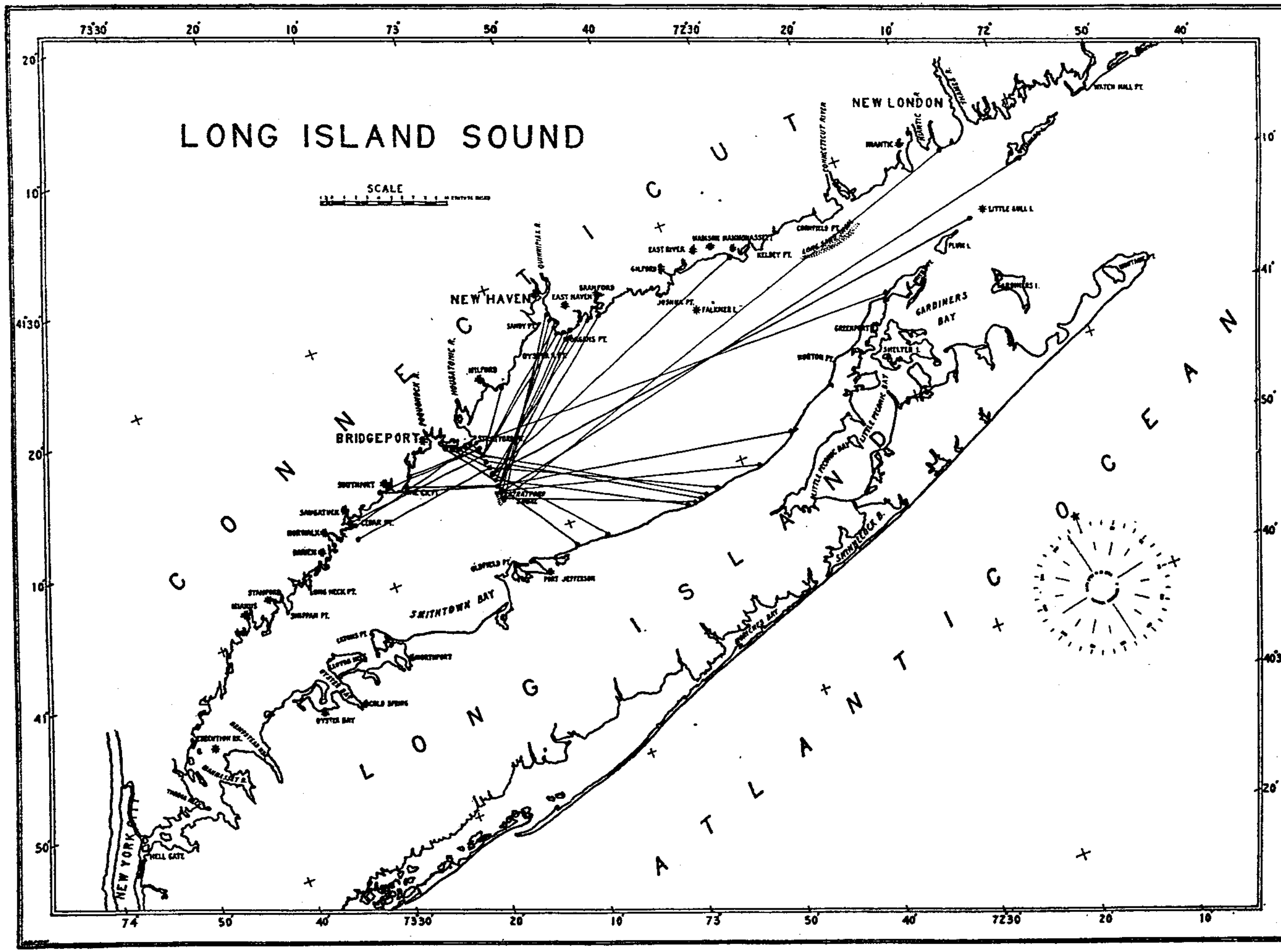

FIGURE 17.—Experiment A, Group 2. Place of release and recovery of bottles put out at low water

Experiment B.—The purpose of this experiment was to determine the drift of the water discharged by the Housatonic during the first and last stages of the ebb tide. Two groups of 50 bottles each were released in the channel at black buoy No. 3. When the bottles of Group 3 were put out at the beginning of ebb tide, the velocity of the current was 1.2 feet per second, and when Group 4 was released at three-quarters ebb the current had attained a velocity of 2.5 feet per second. The distribution of the bottles during the first month is shown in Figures 18 and 19. The majority of Group 3 were recovered to the eastward along the Connecticut shore, from Stratford Point to Joshua Point, a distance of about 20 miles. One of these bottles was the only one of the 500 that succeeded in getting out into the Atlantic Ocean and was recovered on the southern shore of Long Island near Amagansett Lighthouse. The bottles of Group 4 were distributed more widely, and during the first two weeks the majority went to the Connecticut shore and for the most part were found west of Stratford Point as far as Darien, a distance of 17 miles.

Another outstanding difference of this group is the recovery of about one-third of the bottles on the Long Island shore 3 and 4 weeks after they were released. The chief cause of the difference in the distribution of the bottles of Groups 3 and 4 is the velocity and direction of discharge of the Housatonic River at different stages of the ebb tide. At the first quarter of ebb tide, though the current from the river is quite strong, it is met at the entrance by an equally strong ebb current in the Sound, with the result that the river water is carried in an ESE. direction. At the period of about three-quarters ebb, the current from the river has attained considerable strength, while in the Sound we have comparatively slack water. Under these conditions, the river water is discharged straight out into the Sound, oftentimes reaching as far as Stratford Shoal. As the tide in the Sound begins to run flood, this water is forced to the westward and toward the Connecticut shore and is distributed much the same as the drift bottles of Group 4. In the spring and summer the water discharged by the river during the last of ebb tide has a high temperature and low salinity, and its distribution to the westward is responsible, to a great extent, for producing suitable water conditions over this area for the production and setting of oysters.

Experiment C.—(See figs. 20 and 21.) This experiment was planned so as to study the drift of the water close inshore, where the influence of river discharge is negligible. Groups 6 and 8, which were released with the flood tide, were recovered during the first week along the Connecticut shore *east* from Stratford Point to New Haven, in the second week *west* from Stratford Point to the Norwalk Islands, and in the third week on Long Island from Hortons Point to Roanoke Point. In Groups 5 and 7 the distribution of the bottles was very similar, the recoveries having been made a little more to the eastward because they were released with the ebb current. The place and time of recovery of the bottles in experiment C indicate the same general clockwise circulation of the water in Long Island Sound as is shown in experiments A and B.

SUMMARY

The results of the drift-bottle experiments may be summarized as follows:

1. Five hundred bottles were released and of these, 290, or 58 per cent, were recovered in a period of 10 months.

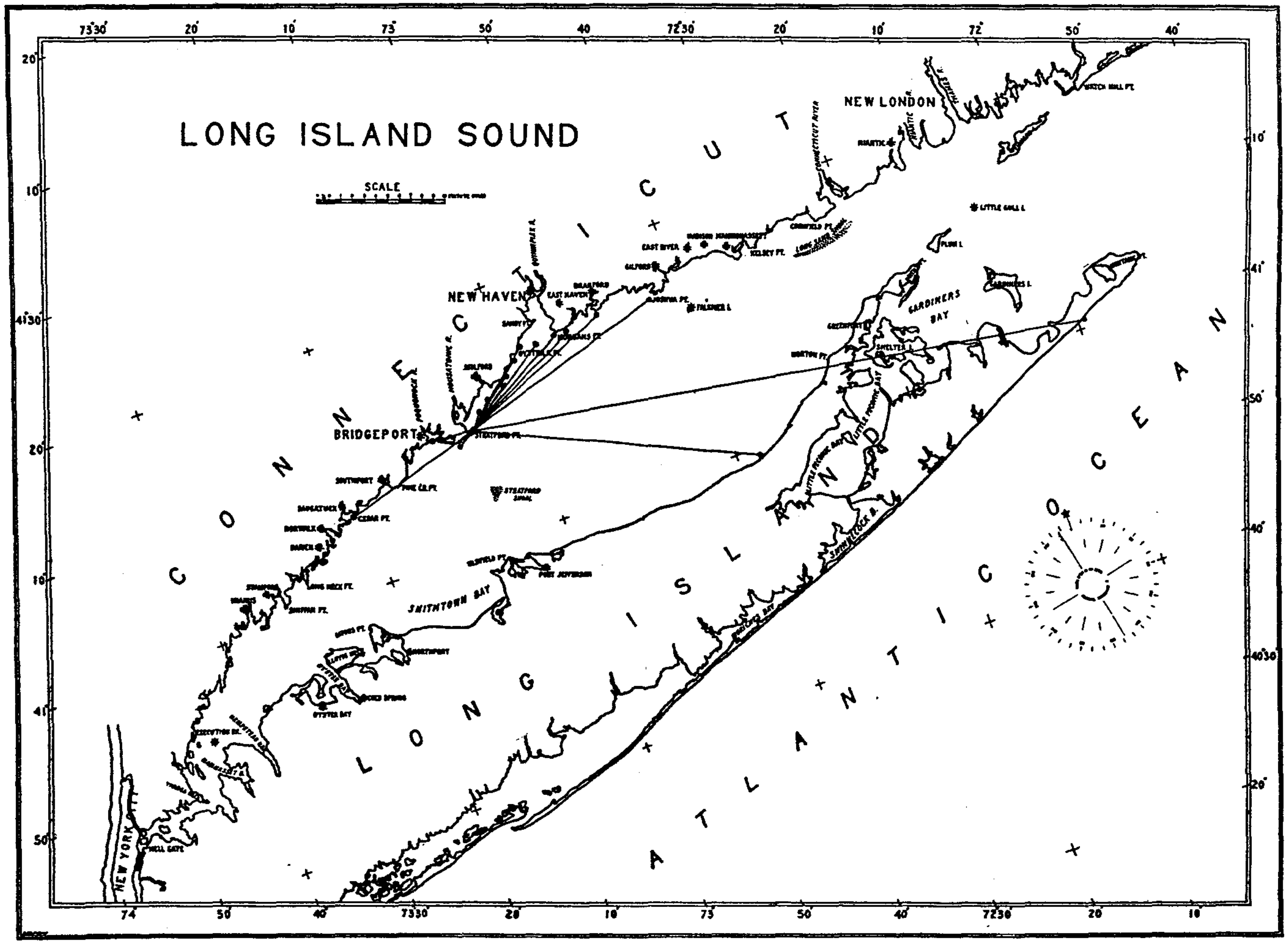

FIGURE 18.—Experiment B, Group 3. Place of release and recovery of bottles put out in the mouth of the Housatonic River at first of ebb tide

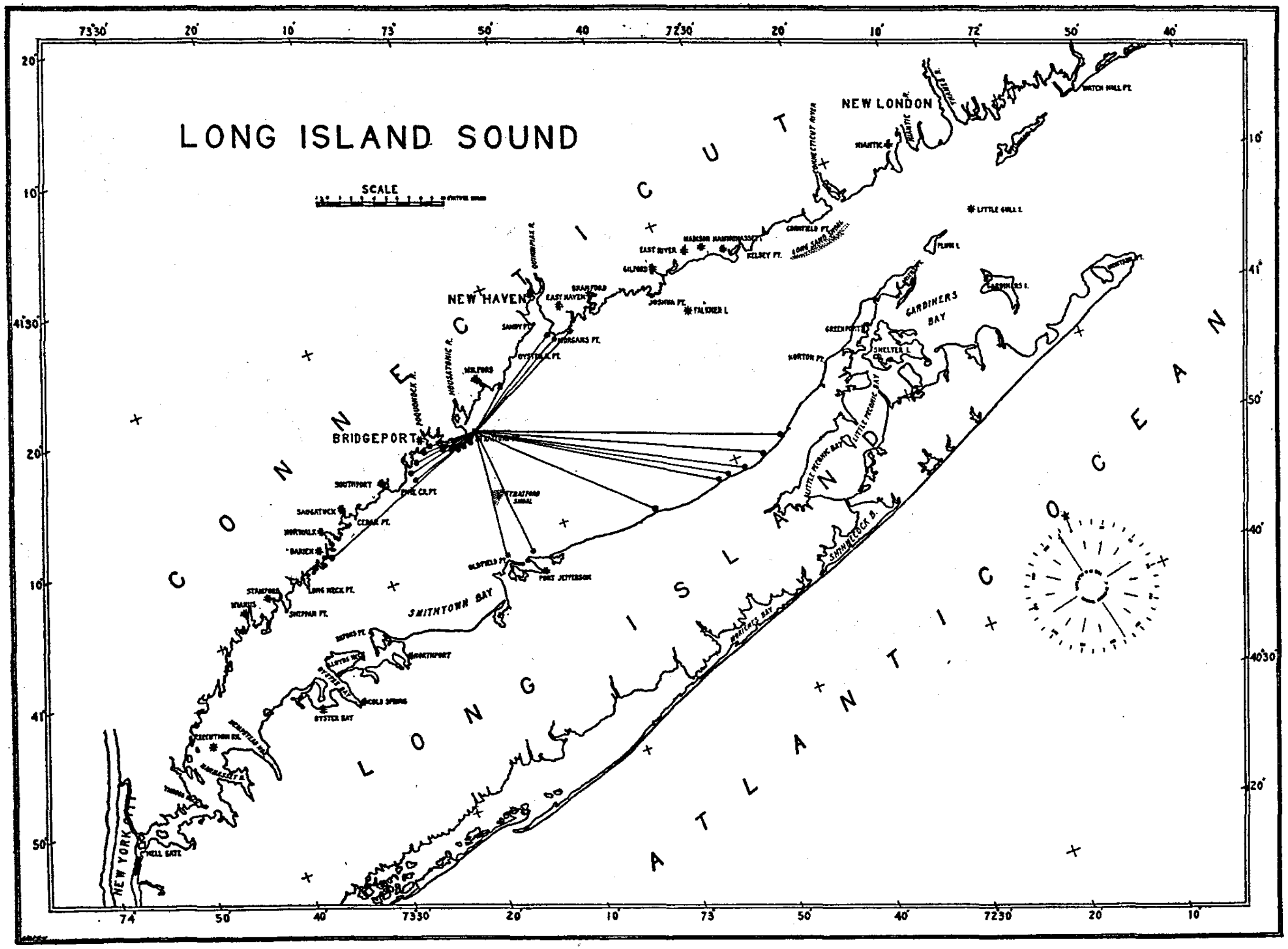

FIGURE 19.—Experiment B, Group 4. Place of release and recovery of bottles put out in the mouth of the Housatonic River at three-fourths ebb tide

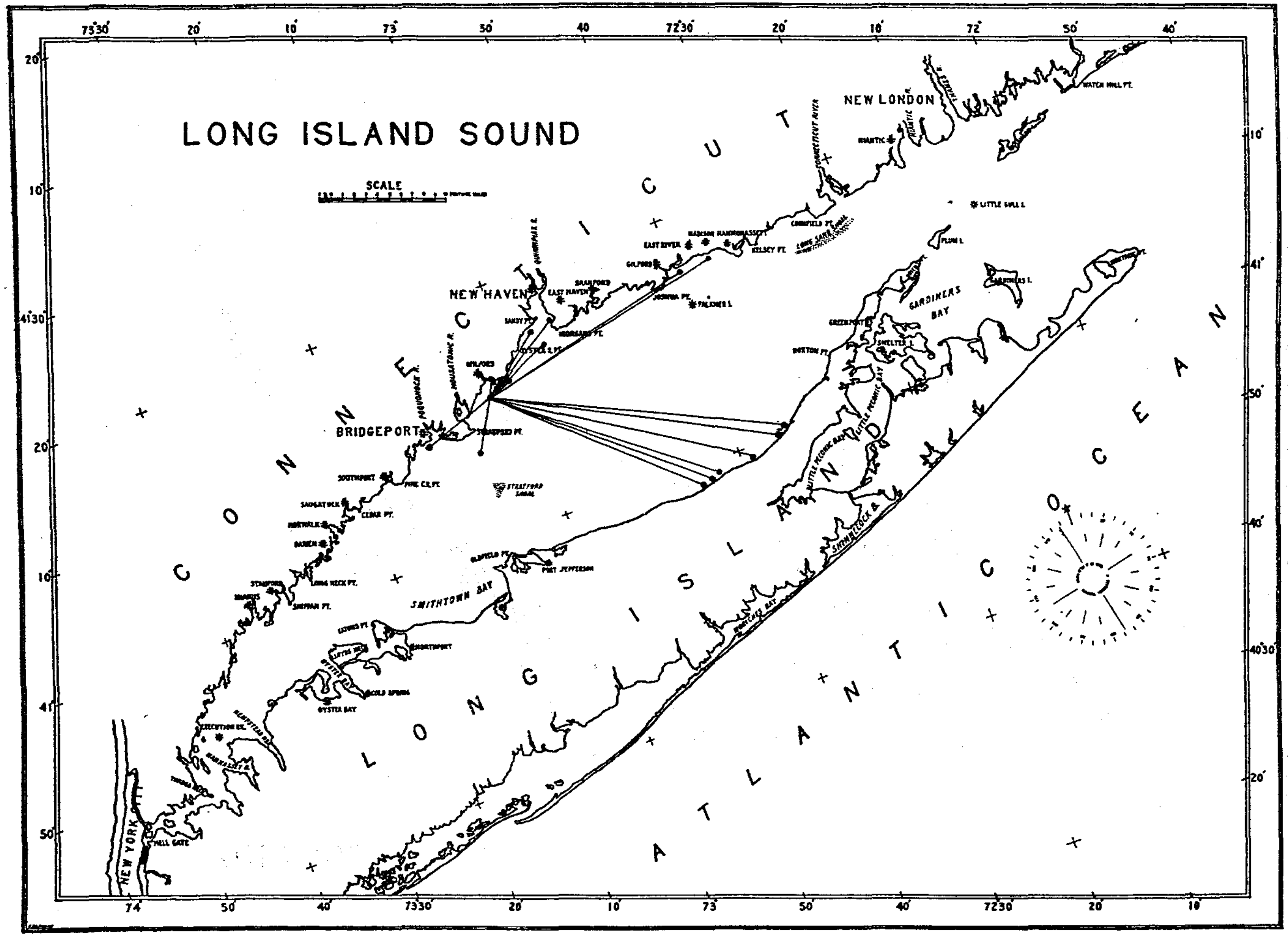

FIGURE 20.—Experiment C, Group 5. Place of release and recovery of bottles put out at Charles Island at one-fourth ebb tide

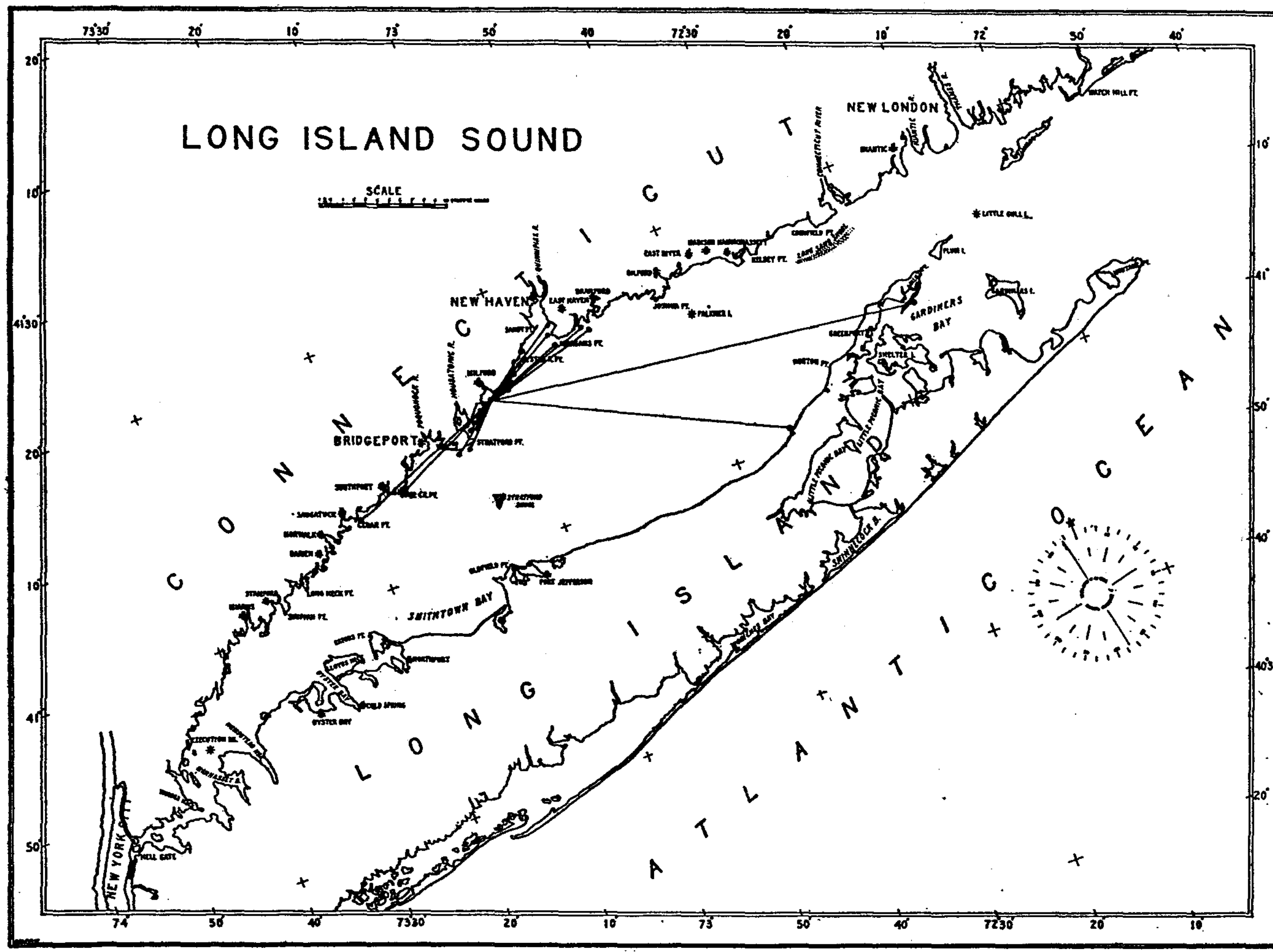

FIGURE 21.—Experiment C, Group 6. Place of release and recovery of bottles put out at Charles Island at one-half flood tide

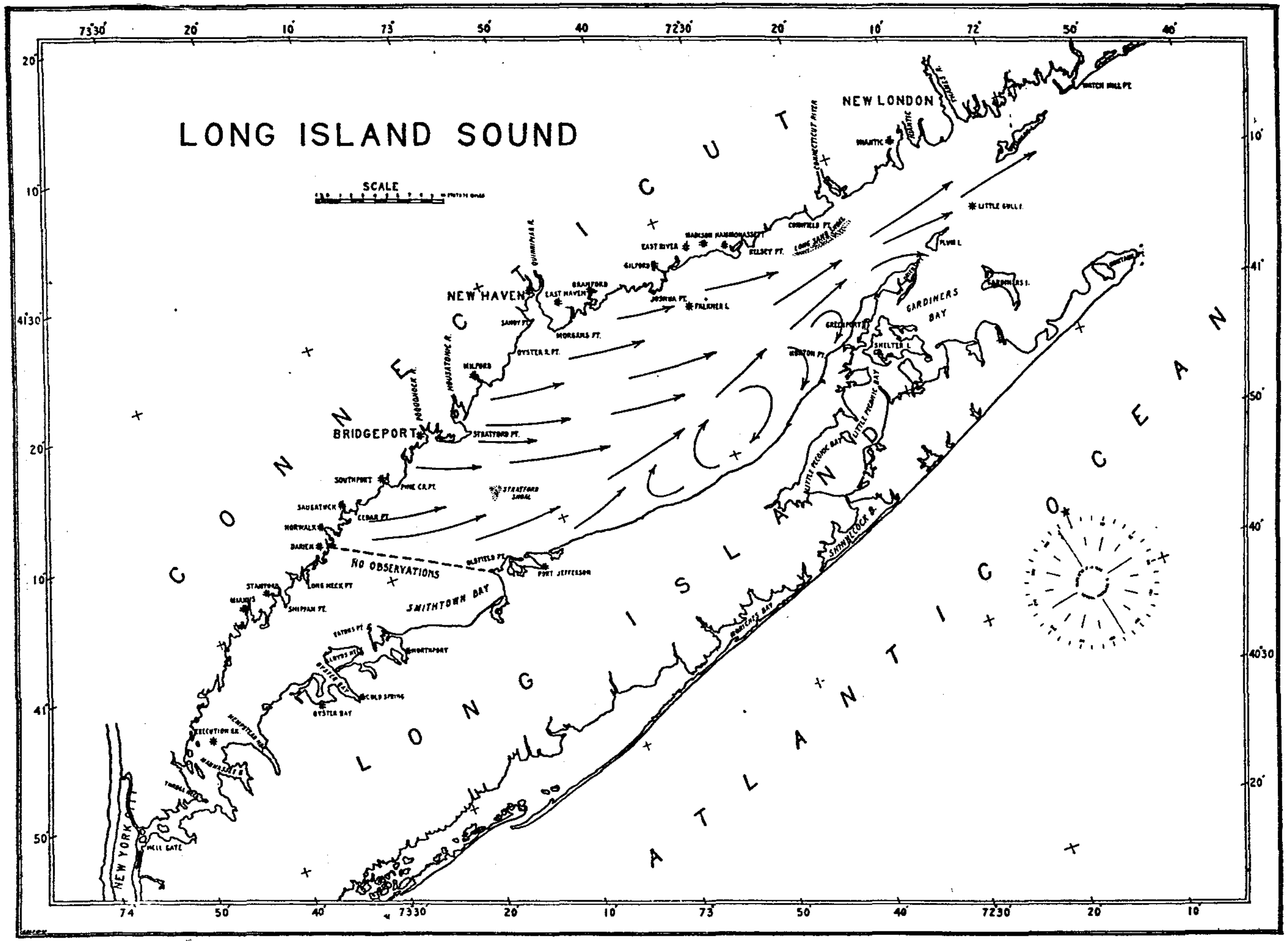

FIGURE 22.—Schematic representation of ebb-tide movement in Long Island Sound as indicated by drift-bottle and current-meter observations

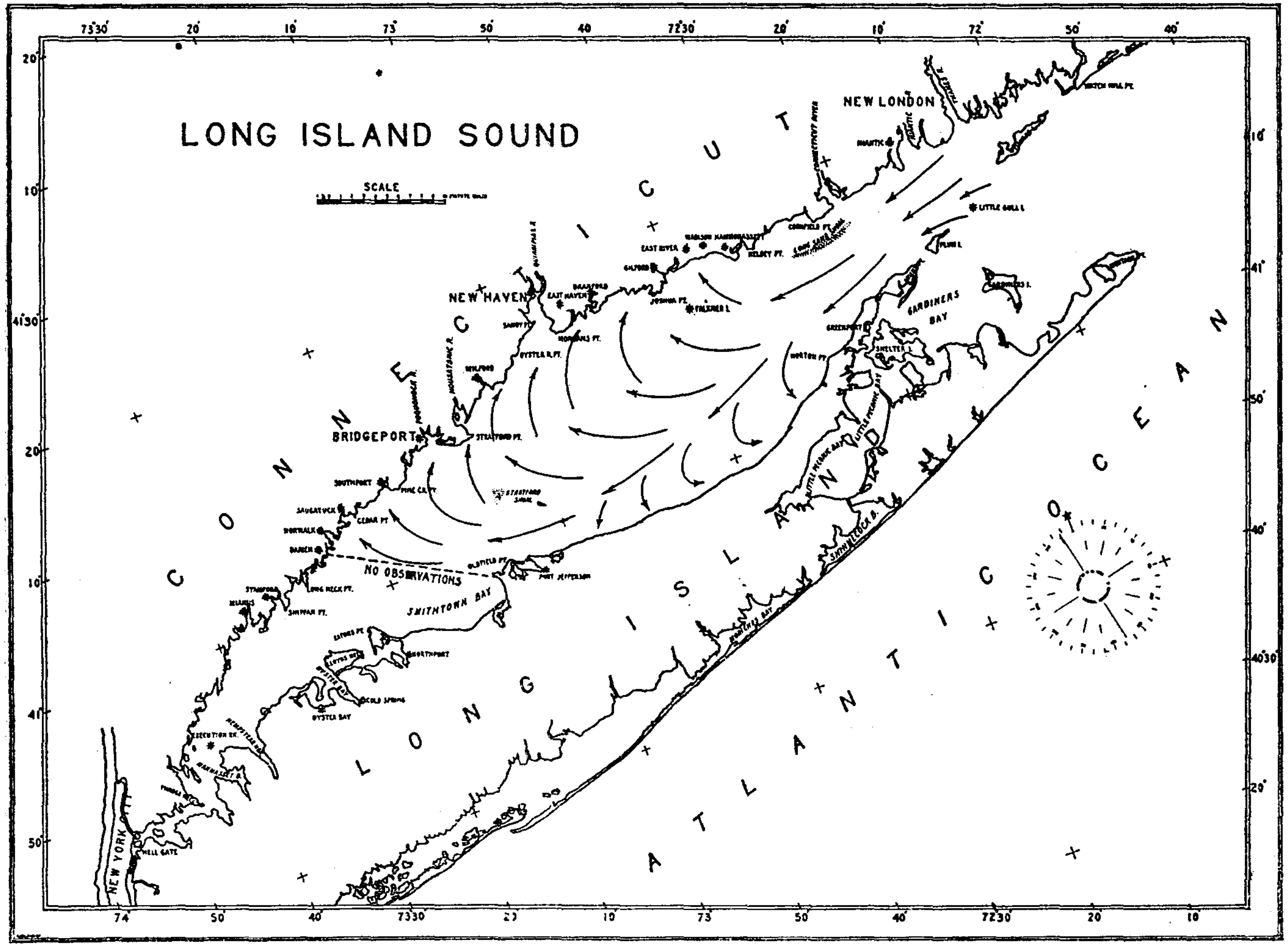

FIGURE 23.—Schematic representation of flood-tide movement in Long Island Sound

2. Seventy per cent of the recovered bottles were collected during the first month, 13 per cent during the second month, and the remainder about equally divided over the next eight months.

3. The bottles recovered during the first month were distributed as follows: 76.7 per cent to the Connecticut shore, 5.3 per cent at the entrance or outside of the Sound, and 18 per cent on the Long Island shore.

4. On the Connecticut shore the bottles were recovered from the Norwalk Islands to Goshen Point, a distance of 65 miles, 15 of which were to the west of the points of release and 50 to the east.

5. In the region at the entrance of the Sound and outside, only 12 bottles were recovered.

6. On the Long Island shore, bottles were recovered from Oldfield Point to Orient Point, a distance of 45 miles.

7. The greatest distance covered by a drift bottle was approximately 150 miles.

8. The fastest recorded drifts were 45 miles in 9 days and 80 miles in 15 days, which give average drifts of 5 and 5.3 miles per day, respectively.

9. A greater percentage of bottles was recovered from the groups released at low water, or with the flood tide, than from those released during the ebb tide.

10. The recovery of the bottles, in relation to time and position, showed a clockwise distribution along the shores of the Sound.

The general movement of the water in Long Island Sound is primarily tidal, resulting in a dominant clockwise circulation, as represented in Figure 24. The rate of movement, as indicated by the drift-bottle records, is approximately 5 nautical miles per day. The existence of such a circulation is of great importance in producing favorable conditions for the growth and propagation of oysters in Connecticut waters. The water coming from the harbors and estuaries on the last of ebb tide is of much lower salinity than that in the Sound and in the spring and summer is considerably warmer. Instead of being carried out to the ocean, it meets the tidal current in the Sound, which has already changed to flood, and is carried to the westward and then spread to the north over the vast oyster region, creating conditions that are favorable for growth and propagation of oysters. In the dumping of mud, sludge, or other refuse, even in the designated areas in the Sound, strict attention must be paid to the stage of tide or the material is liable to be carried and deposited on the oyster grounds and beaches. In all cases dumping should be done preferably at the time of high water in the Sound or during the first 2-hour run of the ebb current. This suggestion is made at this time in view of the recent heavy mortality of oysters that occurred on the beds off Bridgeport as the result of dumping mud from the harbor.

SALINITY

The salinity of the water in Long Island Sound and its estuaries and harbors is determined by two main factors—namely, the discharge of fresh water by the rivers and the inflow of salt water from the ocean. In the Sound the salinity is highest and decreases gradually as we approach the sources of fresh water along the shore. We have a typical example in Figure 25, in which the general distribution of salinity is shown for Milford Harbor and vicinity. The figures are based on the average of

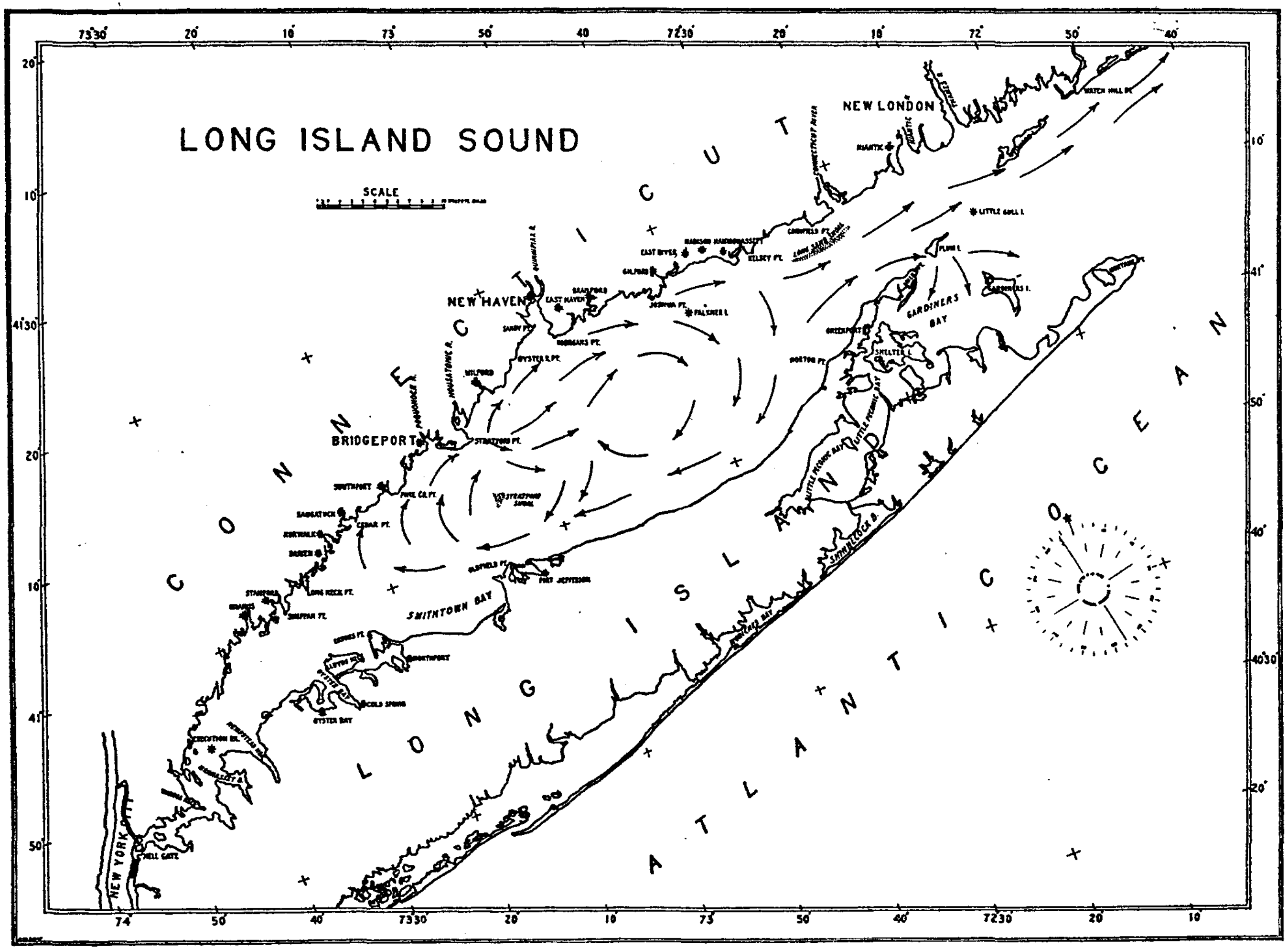

FIGURE 24.—Schematic representation of the dominant circulation in Long Island Sound, as indicated by drift-bottle and current-meter observations

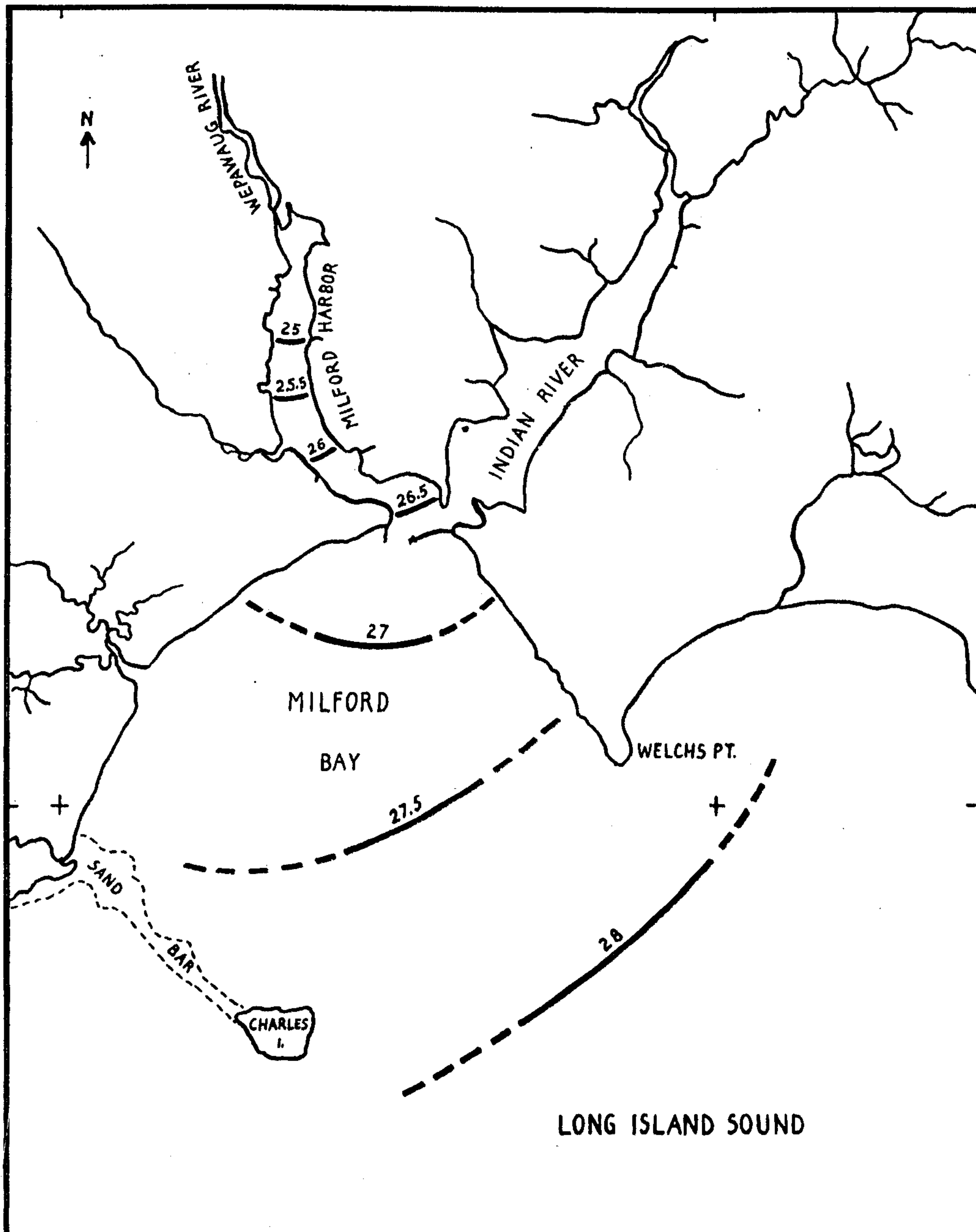

FIGURE 25.—Distribution of salinity, Milford Harbor and vicinity, July 15, 1925, tide at one-third flood

surface and bottom samples taken at each station on July 15, 1925, between 3 and 4 p. m., when the tide was one-third flood. The greatest number of salinity determinations was made at harbor Station No. 2 and at the inshore Sound Station No. 6 at various stages of the tide. The monthly averages at these Stations for July and August of both years are shown in the following table.

TABLE 9.—*Salinity of the water*

Station	Month	Year	Salinity per mille	
			Surface	Bottom
Harbor station No. 2	July	1925	26.32	26.77
Do	August	1925	26.93	27.87
Do	July	1926	27.17	27.47
Do	August	1926	27.59	27.95
Sound station No. 6	July	1925	27.91	28.05
Do	August	1925	28.10	28.21
Do	July	1926	27.70	27.81
Do	August	1926	28.15	28.50

The salinity is rather constant in the deeper waters of the Sound, and the variation from year to year is comparatively small, while in the inshore and harbor areas we find noticeable changes occurring according to the stage and range of tide and amount of river discharge. In several instances observations were made during a complete tidal cycle, from low water to high water and back again. In the following table the series taken at Station No. 2 on August 24, 1925, is given and shows the typical changes in water conditions that occur at various stages of the tide. This is shown graphically also in Figure 26.

TABLE 10.—*Effect of tide on physical conditions, Station No. 2, August 24, 1925*

Tide	Time	Depth (feet)	Salinity	Temperature, °C.	pH
Low water	8 a. m.	0	25.35	20.9	7.2
Do	do	10	27.66	21.8	7.4
Flood	10 a. m.	0	26.78	21.4	7.4
Do	do	11	28.04	20.0	7.8
Do	12 m.	0	27.88	21.9	7.8
Do	do	13	28.10	20.2	7.6
High water	2 p. m.	0	27.75	22.2	8.0
Do	do	15	28.10	21.0	7.4
Ebb	4 p. m.	0	27.66	23.3	7.6
Do	do	13	28.12	22.0	7.4
Last ebb	6 p. m.	0	26.18	24.2	7.5
Do	do	12	27.82	23.0	7.3
Low water	8 p. m.	0	25.50	24.0	7.3
Do	do	10	26.75	23.0	7.2

Since the range of tide on this particular date is but 0.2 foot above the mean range, the changes in water conditions can be regarded as intermediate between those that occur with extreme spring or neap tides. Changes in salinity are least at the time of neap tides and greatest with the spring tides.

The differences in salinity between top and bottom samples were generally less than 1 per mille and naturally were highest at Station No. 1, where fresh water enters the harbor from the Wepawang River, and least at Station No. 6, in the Sound. Occasionally, however, extreme differences were found following heavy rains and with the change of tide from low water to flood. In the first instance the surface was covered with a layer of water from 6 inches to a foot deep, which was virtually fresh or of a low salinity of about 5 parts per mille, while that on the bottom was 25 or more. In the second instance the extreme difference was due to the

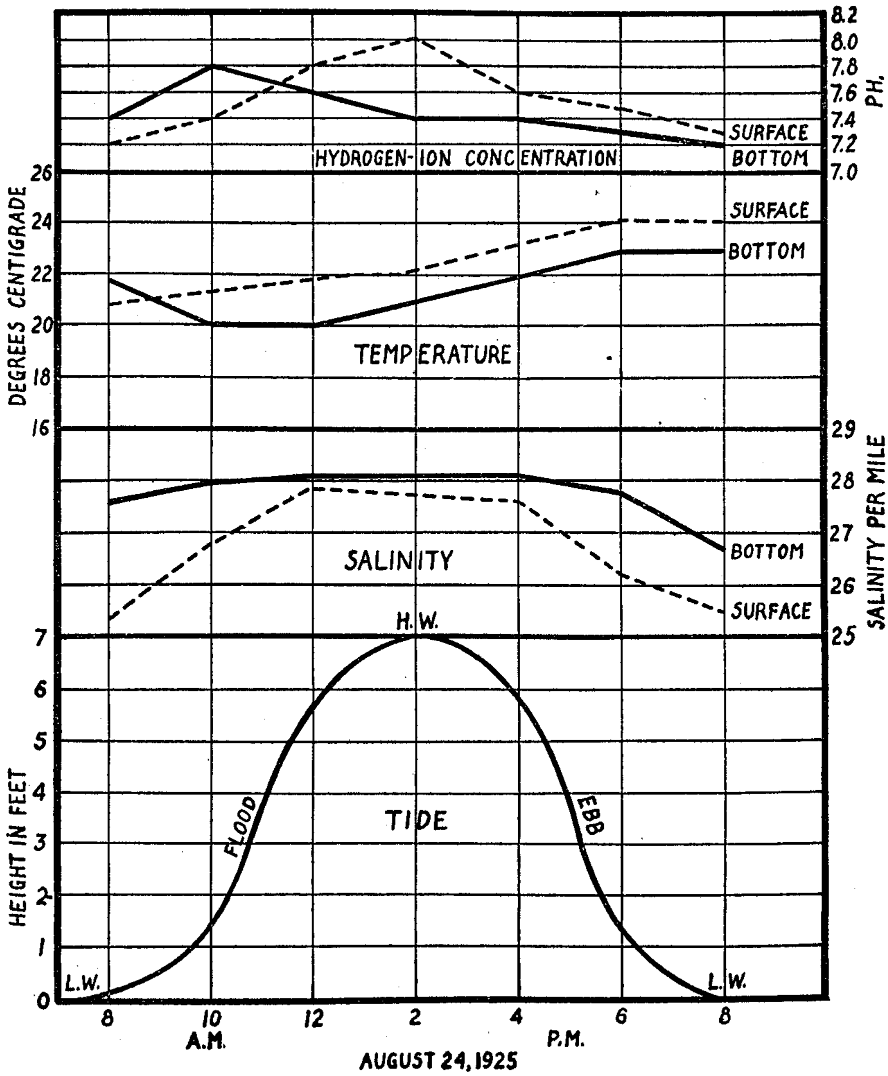

FIGURE 26.—Hourly changes in temperature, salinity, and hydrogen-ion concentration of the water during a complete tidal cycle on August 24, 1925

progression along the bottom of heavy, more saline water with the beginning of flood tide, while that at the surface was still running at ebb or at low slack water. Samples taken at such times showed a difference in salinity of from 2.5 to 3 parts per mille between the surface and bottom at a depth of 10 feet.

The range of salinity in the harbor in 1925 was from 4.5 to 28.12 per mille, while in 1926 the range was from 10.48 to 28.66 per mille. At the inshore Sound Station

No. 6 the range of salinity in 1925 was from 27.54 to 28.50 per mille and in 1926 from 27.36 to 28.74 per mille. These figures apply only to the summer months, July and August, when conditions are comparatively stable. According to Galtsoff (unpublished report), there are seasonal variations in the salinity of the Sound waters, the most noticeable of which is the freshening of the water at the time of spring floods in April and May, when the salinity is lowest; while during the cold months the salinity was found to increase gradually and reached the maximum for the year in January. He found that in these waters the seasonal fluctuation in salinity was a regular process, which repeated itself with certain constancy from year to year. At his station at the entrance to Bridgeport Harbor the annual range in salinity in 1922–23 was from 24.7 to 27.8 per mille, an average of 26.2 for the year.

HYDROGEN-ION CONCENTRATION

The hydrogen-ion concentration of the water was determined for each station by the colorimetric method and the values expressed in pH, in which no correction has been made for salt error. In this locality the water is naturally alkaline and during the summer ranges from a pH of 7.2 to 8.4. In plotting the average readings for each station, we find that the pH increases from 7.6 at Station No. 1 to 8.2 at Station No. 6 in the Sound. The lowest pH values were found in samples taken at low tide following heavy rains, and the highest in afternoon samples taken in the harbor near the time of high water. The pH was found to vary with the time of day, depth, stage of tide, and amount of river discharge. An example of the surface and bottom changes in pH during a complete tidal cycle is shown in Figure 6 for a series of observations taken on August 24, 1925. In samples taken in the morning the pH of the surface water generally was found to be a little lower than that of the bottom water. In the afternoon the reverse was true and the pH of the surface water was from 0.1 to 0.2 higher than it was on the bottom, probably as a result of increased photosynthesis in the warmer surface layer. In considering the characteristic changes in pH during both summers, we find that during July the average pH value was 7.8, while in August the readings became higher and ranged from 8 to 8.2.

RIVER DISCHARGE

The importance of river discharge in the ecology of the oyster is shown clearly by the fact that oysters are found growing naturally only in those partially inclosed bodies of water along the coast where the salinity is reduced considerably by the drainage of fresh water from the land. On its northern shore Long Island Sound receives the drainage from virtually the entire State of Connecticut and a large portion of Massachusetts, Vermont, and New Hampshire, and it is here that we find thousands of acres suitable for the growth of oysters, as shown in Figure 2. There are over 30 coastal rivers that discharge into the Sound, of which the Connecticut and Housatonic are the largest.

The Connecticut River receives the drainage from an area of approximately 11,000 square miles and the Housatonic from 1,500 miles. The lowest point for which records of river discharge are available is Sunderland, Mass., on the Connecticut River, and Falls Village, Conn., on the Housatonic River. The mean monthly discharge of the rivers at these points is shown in Figure 27 for the period from April until August in the years 1924, 1925, and 1926. The quantity of water discharged shows a marked variation from month to month and from year to year and is representative, in a general way, of the changes in salinity that occur in Long Island Sound

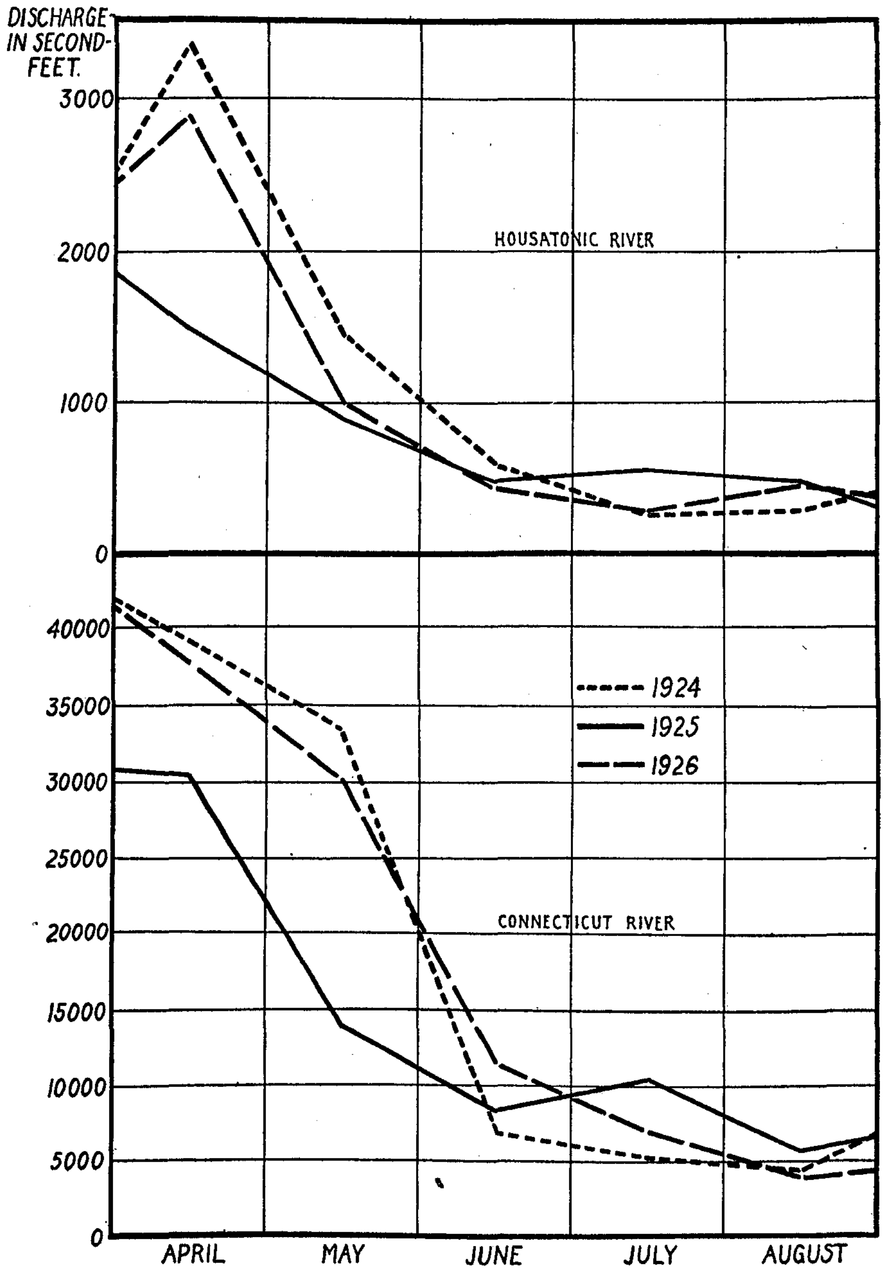

FIGURE 27.—Quantity of water discharged monthly by the Housatonic River at Falls Village, Conn., and by the Connecticut River at Sunderland, Mass., for the period April to September, 1924 to 1926

during these periods. Similarly, the effect of river discharge on the temperature of the water in the Sound varies according to the quantity and temperature of the water emptied into it. According to Collins (1925), the mean temperature of the river water during these months is generally from 1° to 3° F. below the mean air temperature. If we use this relationship as the basis for estimating the temperature of the river water and also take into consideration the amount of river discharge, we find that in 1924 and 1926 the quantity of water emptied into Long Island Sound was much greater than in 1925, and its temperature was decidedly below normal, while the smaller discharge in 1925 had a temperature several degrees above normal. This applies especially to the months of April, May, and June, while during July and August, 1925, the river discharge was greater and its temperature approximately 71° F., which is virtually normal temperature for this period. During these summer months the river water reaches its maximum temperature for the year, which generally is greater than the mean monthly air temperature for each drainage basin. The river discharge in July, 1925, served to reduce the salinity of the water in Long Island Sound and to increase its temperature to a greater extent than did the smaller discharge in 1926. The tables of salinity and water temperatures for these two months show clearly how the amount and temperature of river discharge affected these conditions.

The prime factors influencing the amount of river discharge are quantity, intensity, and distribution of precipitation over each drainage basin. Records of precipitation along the coast must be taken into consideration, together with the discharge of these two large rivers, in order to arrive at an approximation of the quantity of fresh water that directly and indirectly, is emptied into Long Island Sound. Along the coast of Connecticut is a belt of approximately 1,300 square miles that is drained by a great many small rivers, and for this region precipitation records must be used because figures of river discharge are not available.

During the spring and summer months the drainage of fresh water from an area of over 13,000 square miles to the north of Long Island Sound is important because (1) it increases the temperature of the water over the oyster beds and (2) brings down organic matter and mineral salts, both of which increase the production of plankton

BIOLOGICAL OBSERVATIONS

CONDITION OF THE GONADS OF THE OYSTER

Oysters in Milford Harbor were found to be ripe in the period from July 1 to 15, the exact time varying in accordance with the previous water temperatures. In 1925 the gonads of the oysters were fully ripened by June 29, while in 1926 and 1927 this condition was not found until nearly the middle of July. By stripping the oysters, a small quantity of ripe eggs and sperms almost always can be found by July 1, but this can not be taken to indicate that the reproductive products are fully developed. The test employed for this purpose, which proved most reliable, was to place at least a dozen oysters in water that was pumped at high tide and warmed to a temperature of at least 25° C. Under these conditions ripe oysters invariably spawned and discharged the bulk of their products, while those that were not fully ripe generally did not spawn or, at most, spawning consisted in a few contractions of the shell and the release of but a small quantity of spawn. According to Galtsoff (unpublished report), the addition of sperm to the water will induce spawning, and, in case the oysters failed to spawn voluntarily, a small quantity of sperm from two to three oysters was added in order to accelerate the process in case the temperature was not a sufficient influence. Samples of the oysters always were examined before and after the tests so as to determine the approximate amount of spawn retained or released. In these examinations several transverse sections were cut through the body of the oyster so that the thickness of the reproductive tissue could be seen easily. In comparing these sections from year to year a very noticeable difference was found in the quantity of spawn in oysters taken from the same bed each season. In the sections cut anterior to the heart the layer of reproductive tissue surrounding the liver was found to vary

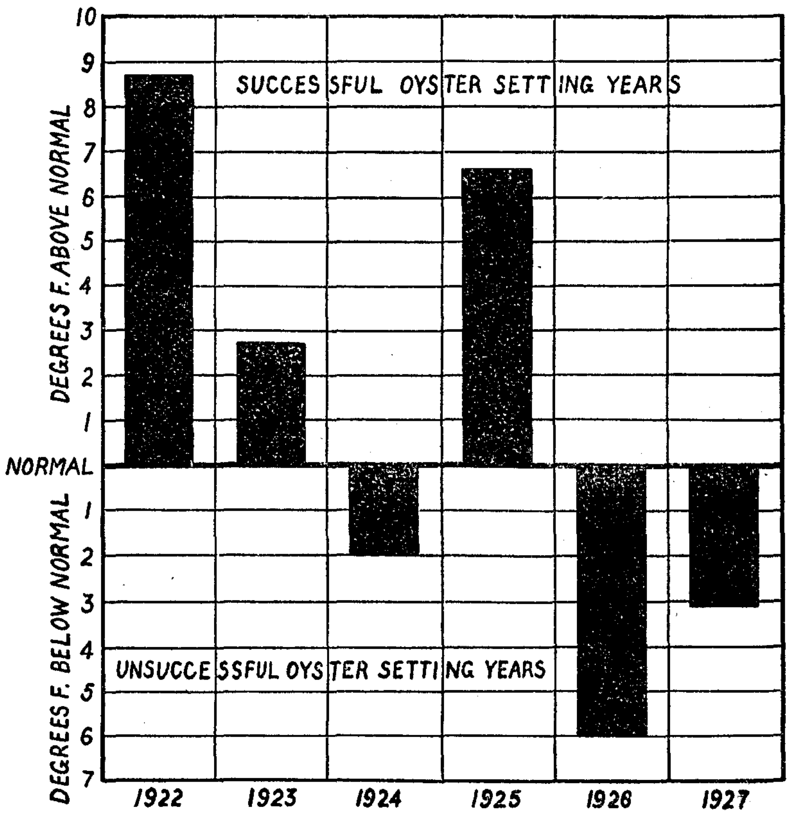

FIGURE 28.—Total air temperature departures from normal at New Haven, Conn., for the period April 1 to August 1

from over 1.5 centimeter in 1925 to 0.5 centimeter and less in 1926 and 1927. A noticeable difference was also found in the consistency of this layer, which in 1925 was extremely soft and milky, while just the opposite condition was found the other two years.

In order to determine the cause of this annual difference in the quantity and ripeness of the spawn as observed on July 1, water and air temperatures were examined during the preceding spring months. By using the departure of air temperature from normal as a basis and estimating the approximate water temperatures at 2° below the temperature of the air, we find that for the period April to July 1 the water temperature in 1925 was several degrees above normal, while in 1926 and 1927 it was decidedly below. This is illustrated by Figures 8 and 28, which show the monthly and total departure of air temperature from normal for this period during these years and also for 1922, 1923, and 1924. In Figure 28 the total monthly departures for this 4-month period has been given because of the cumulative effect of water temperature on the development of the gonads during this interval. It can be seen clearly that in 1922, 1923, and 1925 the water temperature was *above* normal, and we know, because of the set obtained, that spawning in Long Island Sound was successful in these years. In 1924, 1926, and 1927 the water temperature was *below* normal and setting was a failure This evidently was due to unsuccessful spawning, because virtually no oyster larvæ were found in the water. The success or failure of spawning in Long Island Sound apparently depends upon the quantity of eggs and sperm developed by the oysters each year. Since fertilization of the eggs takes place outside of the oyster and is a matter of chance, it is reasonable to expect that the percentage of eggs fertilized and number of larvæ and spat produced will vary according to the amount of spawn released. A small increase or decrease in the number of eggs or spawn in a single oyster becomes of importance when we realize that it is multiplied by the number of oysters on the beds, which is from approximately 125,000 to 250,000 for each acre planted.

It is likely that the fullness of gonad development is dependent on the amount of food consumed by the oyster. We know that the process of feeding consists in filtering water through the gills, and that the amount filtered is controlled by temperature. Galtsoff has measured accurately the amount of water filtered by the oysters at various temperatures. Taking his figures (Galtsoff, 1928), we can estimate the differences in quantity of water filtered by the average oyster during cold or warm seasons. The period in which we are interested extends from the beginning of feeding (about April 15, when the water temperature reaches 7° C.) until the time of spawning (the latter part of July). During this period the approximate number of liters or quarts of water filtered by an average oyster at normal water temperatures is given in the following table:

TABLE 11.—*Approximate quantity of water filtered by an average oyster at normal water temperature*

Month	Quantity filtered		Mean temperature, ° C.
	Liters	Quarts	
April	25	26	[1] 9
May	408	431	12
June	816	862	17
July	995	1,051	20
Total	2,244	2,370	

[1] 15 days only.

As a result of the monthly and annual variations in water temperature that occurred from 1922 to 1927, the quantity of water filtered shows a corresponding variation, which is presented in the following table:

TABLE 12.—*Approximate number of liters of water filtered by an average oyster in Milford Harbor*

[S=successful setting; F=failure in setting]

Year	Liters of water per month				Total
	April	May	June	July	
Normal	25	408	816	995	2, 244
1922	51	612	893	995	2, 551 S
1923	46	408	918	969	2, 341 S
1924	26	326	765	995	2, 112 F
1925	102	408	969	969	2, 448 S
1926	0	357	688	995	2, 040 F
1927	10	325	765	1, 005	2, 105 F

In comparing the various years, we find that when spawning and setting were successful, each oyster filtered from 200 to 500 liters of water more during the 4-month

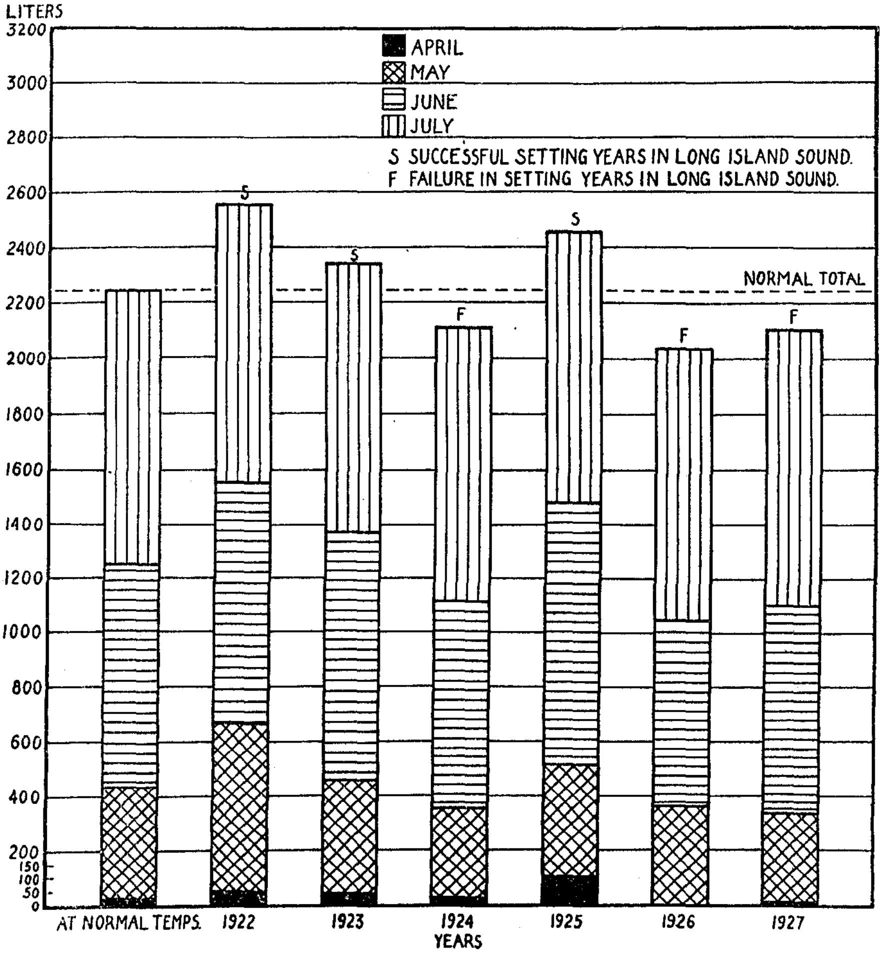

FIGURE 29.—Approximate quantity of water filtered monthly by an average oyster previous to the time of spawning. The quantity filtered during the years 1922 to 1927 is shown in comparison with the quantity that would be filtered under normal water-temperature conditions

period than it did during the years when spawning apparently was a failure. The difference in total quantity of water filtered each year is shown clearly in Figure 29.

The average of the "successful" years shows that the total quantity filtered by one oyster during this time was 203 liters more than the amount filtered at normal temperatures, while the average of the "failure" years was 159 liters *less* than the normal amount. In the following table the average liters of water filtered monthly and the total number of liters filtered during the successful and unsuccessful years are given.

TABLE 13.—*Comparison of the quantity of water filtered by an average oyster during setting and non-setting years in Long Island Sound*

Setting	Average number of liters					Departure from normal, liters
	April	May	June	July	Total	
Success	66	476	927	978	2, 447	+203
Failure	12	336	739	998	2, 085	−159

During the three years when air and water temperatures were above normal we should expect to find a greater quantity of spawn in the oysters because of the direct influence of higher temperatures on the development of the gonads and because of the greater feeding activity on the part of the oysters. The time when oysters are found to be ripe also varies from year to year and can be correlated with previous water temperatures. The condition of the gonads observed in 1925, 1926, and 1927 support these views and show that the development of the gonads was greater and time of ripening earlier when water temperatures were above normal, as in 1925, while the opposite was true in the other two years, when temperatures below normal occurred.

TIME OF SPAWNING

The time when the ripe oyster discharges its spawn into the water depends largely upon temperature. Studies of oyster spawning in Milford Harbor, as well as those of Galtsoff (unpublished manuscript, 1926), Churchill (1919), Nelson (1924), and Gutsell (1922), show that spawning seldom occurs when the water temperature is below 20° C. In many instances in 1925 and 1926 spawning was observed to take place in tanks and floats at temperatures ranging from 20° to 27° C. The oysters used in these experiments came from Milford Harbor and the offshore beds in Long Island Sound. It was found that those from the Sound, where the water temperature is much lower than in the harbor, spawned in about half an hour at 20° to 22° C., while the oysters from the warmer harbor waters required several hours' exposure to this temperature before spawning occurred, or, on the other hand, they could be induced to spawn in half an hour by increasing the temperature from 23° to 27° C.

The time of spawning of the oyster on the beds was determined, first, by examination of the plankton samples for the presence of larvæ 24 to 48 hours old and, second, by observations as to the quantity of spawn in the oysters. In Connecticut waters there generally occur two spawnings, the first being very light and occurring about the middle of July, while the second is heavier and occurs about the 1st of August. The time of spawning was found to vary somewhat from year to year in accordance with water temperature and tidal conditions. The dates on which spawning occurred in 1925 and 1926 and its relation to tide and temperature are shown in Figure 30. Heavy and complete spawning of the harbor oysters occurred on July 13 in 1925, but not until August 1 in 1926. Similarly, spawning in Long Island Sound at Station No. 6 was 17 days earlier in 1925 than in 1926. In 1925 spawning occurred more than

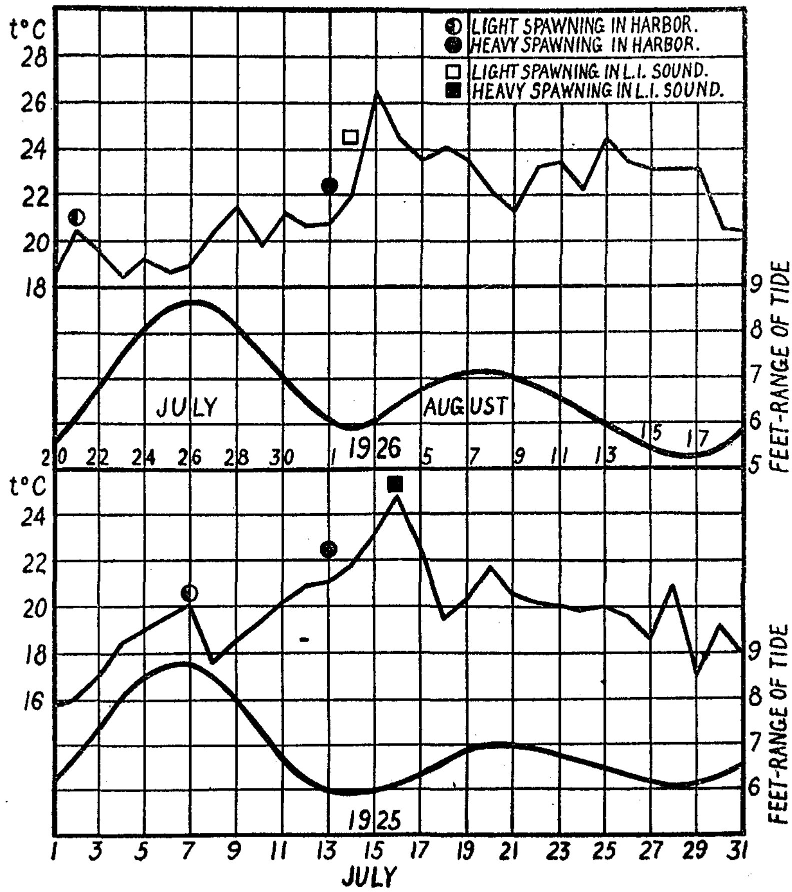

FIGURE 30.—Correlation between range of tide, temperature, and the spawning of the oysters during the summers of 1925 and 1926

two weeks earlier than has been observed during the past seven years and was due to the higher water temperature and early ripening of the oysters during July of that year. Though in 1926 the water in the harbor reached a temperature of 22.4° C. on July 10, spawning did not occur, as the oysters were unripe at this time. During both years the heaviest spawning of the oysters in the harbor was found to occur after the water had reached and maintained for a few days a temperature of from 20° to 21° C.

The part played by the tide in increasing water temperatures during July and August has been discussed previously, and its relation to the time of spawning in 1925 and 1926 is shown clearly in Figure 30. In both years, the majority of the oysters spawned at the end of the July "full-moon tidal period," when the water was brought to a favorable spawning temperature. In 1927, spawning of the oysters in Milford Harbor was studied in relation to the moon's phases and the range of tide. The oysters were found to have spawned (as indicated by the presence and age of larvæ) on July 22, which was also at the end of the "full-moon tidal period," or eight days after the time of full moon. Fifteen days later, setting was found to occur not only in Milford Harbor but also in Southport Harbor, Conn., and several other inshore areas that were examined. The relationships between the moon's phases and time of spawning depends largely upon the range of tide occurring during any particular phase. Whether spawning will take place during or at the end of the periods of greater tidal range is determined by the water temperature at the beginning of the period and the weather conditions accompanying it. The effect of the tide on the trend of water temperatures has been discussed on page 449.

In this connection, the studies of J. H. Orton in 1925 at Falmouth, England, on the lunar periodicity in the spawning of the European oyster (*Ostrea edulis*) are very interesting. He found that spawning of the European oyster can be correlated with the moon's phases but was unable to determine the direct factors controlling spawning at such times, though he suggests tide, moonlight, food, temperature, and sunshine. Unfortunately, he did not obtain water-temperature records for the locality in which the observations were made, and consequently, the relationship between increase of water temperature and range of tide could not be determined. We know from the tide tables that the spring range of tide at Falmouth, England, is nearly 16 feet, more than twice that in Milford Harbor. Under these conditions, it is likely that the water over the Falmouth beds would show a marked increase in temperature during spring tide periods because of the warming of the water on a greater area of tidal flats at such times. It is interesting to note that he found the maximum percentage of recently spawned oysters in the week after full moon, which corresponds very closely to the spawning observations made at Milford on the American oyster. Also, the first and apparently heaviest spawning at Falmouth occurred on virtually the same date in July, 1925, as did the heavy spawning at Milford. On the basis of our observations, we can state that oyster spawning in Milford Harbor occurred at the end of the full moon tidal periods because of the increase in water temperature that is produced as a result of the greater range of tide during this period. The effect of the moon on the spawning of the American oyster is only indirect through the changes it produces in the vertical and horizontal movement of the water over the oyster beds. The effect of the tide on water temperatures and spawning in any locality depends largely upon hydrographic conditions and especially the tidal range and area of tidal flats.

Another important observation made on oyster spawning in the harbor was that the discharge of spawn occurs near or at the time of high water. From July 21 to 29, 1926, the water temperature on the last of ebb tide and at low water was often from 20° to 26° C., and yet the oysters failed to spawn. The same oysters, when placed in water pumped at high tide and warmed to the same degree, spawned in a very short time. It was observed also that oysters kept in the floats always spawned near the time of high water, at temperatures ranging from 20° to 24° C., and never at low water, though it was several degrees warmer. In analyzing the factors of temperature, salinity, and hydrogen-ion concentration at the time when spawning occurred, it was found that the hydrogen-ion concentration or pH value of the water showed the greatest difference. In all the observations but one, the water had a pH value ranging from 7.8 to 8.2 when spawning occurred, while in the exceptional case the pH was 7.6 and the water temperature 23° C.

As shown in Figure 26, the pH value of the water in Milford Harbor is lowest at the time of low water, when the pH is approximately 7.2, and is highest near the period of high water, when the pH averages about 8.2. The failure of the oysters to spawn at low tide, when the water temperature is often above 20° C., evidently is due to the low alkalinity of the water at this stage of tide, as indicated by the pH readings. Spawning was found to occur near the times of high water at this same temperature, when the alkalinity was much higher or when the pH value was 7.8 or above. In 1925, the heaviest spawning took place on the day when the water at the times of high tide had attained a temperature of 20° and 21.5° C., and in 1926, when the temperature at the same stage of tide was 20.5° and 21° C.

In summarizing the studies of spawning in Milford Harbor, it is concluded that the most important controlling factors are the temperature of the water, the range of tide, and the hydrogen-ion concentration.

OCCURRENCE AND DISTRIBUTION OF THE LARVÆ

For several years, studies of the oyster larvæ in Connecticut waters have been carried on by various investigators of the bureau (Churchill and Gutsell, unpublished reports), and extensive plankton collections were made in the region between Bridgeport and New Haven. In these collections the abundance and distribution of the larvæ were extremely irregular, and in the majority of the samples no larvæ could be found. In locating stations over this comparatively large area such a variety of changes in the physical conditions is encountered that the results at each station are hardly comparable and there are insufficient data for the study of any one locality.

The plan that was put into operation in 1925 consisted (1) in the rehabilitation of a natural oyster-growing body of water, such as Milford Harbor, by the establishment of spawning beds and (2) in an intensive study of the occurrence and distribution of the oyster larvæ in this restricted area in relation to the physical conditions existing there. Both quantitative and qualitative plankton samples were collected, together with data as to temperature, salinity, and stage of tide. The oyster larvæ were found in two rather distinct groups, the first of which was rather small in number and appeared on July 8 and 9 in the straight-hinge stage, which indicates that light spawning occurred on July 7; while the second or larger group of larvæ was found in the water on July 14 following a heavy spawning of oysters on July 13. The duration of the larval period in the first group was approximately 13 days, with a mean daily water temperature of 20.8° C., while in the second group the period from spawning to setting was 16 days at a mean water temperature of 20.6° C. The completion of the larval period, with setting of the larvæ on the 20th and 29th of July in 1925, occurred approximately two weeks earlier than had been observed at any time previous and can be attributed to the higher water temperatures of that year.

In 1925, 130 plankton samples were collected at the various stations from both the surface and bottom. The results obtained from these collections were much different than had been expected, and the oyster larvæ not only were scarce but occurred very irregularly. The majority of the larvæ found were either a day or two old or nearly fully developed and ready to set. The number of larvæ at any station, in proportion to the intensity of setting, was extremely small, as, for example, at Station 3, where the total number collected in a period of several weeks scarcely reached 100, while in the same spot many thousands of them were found later attached to the shells and brush. In studying the occurrence of the larvæ in relation to the stage of tide when the sample was taken, a rather definite relationship was found to exist; namely, that the larvæ were most abundant near and at the period of low water and generally absent at the time of high water. In 1926 the methods of collection were changed and planned so as to permit study in greater detail of the occurrence of the larvæ in relation to stage of tide. For this purpose two quantitative methods of plankton collection were employed, one of which was to take 3 samples of 50 gallons each from the top, bottom, and middle zone at each stage of the tide, and the other was to pump the water continuously from a point 1 foot below low-water mark (which corresponded to the level of the spawning bed) and determine the number of larvæ present at each hour of the day and height of the tide. In 1926 the larvæ were found in the samples at a much later date and again occurred in two rather distinct "schools" or groups following light spawning on July 22 and heavy spawning on August 1. The larval period of the first group was approximately 16 days at a mean temperature of 21.3° C., and of the second group was 14 days at 23.2° C. During this summer, more than 185 plankton samples were collected, the majority of which were taken in Milford Harbor within a short distance of the spawning bed and especially over the area of heaviest setting.

DISTRIBUTION

The abundance of the larvæ from the surface of the water to the bottom was found to vary according to the stage of tide, which for convenience was divided into three arbitrary periods—namely, low water, intermediate, and high water—each of which covers an interval of four hours. The low-water period covers the last two hours of ebb tide, slack water, and the first two hours of flood tide. The intermediate period included the two hours of flood tide and two hours of ebb tide when the tide was approximately halfway between high and low water marks. The high-water period consisted of the last two hours of flood tide, slack high water, and the first two hours of ebb tide. At mean range of tide the vertical movement of the water during the low-water period is approximately 1½ feet; during the intermediate period, 3½ feet; and during the high-water period, 1½ feet.

In 140 samples made with reference to the tide the larvæ were found to be most abundant during the low-water period, virtually absent during the intermediate period, and present only in small numbers during the high-water period. In the following table the average number of larvæ per 50 gallons that were collected during three complete tidal cycles from August 11 to 13, 1926, is given as an example. In this table the counts of the larvæ include only those that have passed the straight-hinge stage, or, in other words, "umbo" larvæ that were from 3 days old to setting size; and, of these, the majority in nearly every case were found to be in late stages of development and within a few days of setting. The only time when umbo larvæ of different ages were found swimming in the water was at the time of low slack water and even then the older forms predominated.

TABLE 14.—*Vertical distribution of oyster larvæ in Milford Harbor in relation to the stage of tide, August 11 to 13, 1926* [1]

Period of tide	Average number of larvæ per 50 gallons			
	Surface	Mid-zone	Bottom	Total
Low water:				
Last ebb	2	7	12	21
Slack water	15	18	19	52
First flood	22	13	6	41
Intermediate:				
Flood	1	1	3	5
Ebb	0	0	1	1
High water:				
Last flood	0	2	2	4
Slack water	3	3	7	13
First ebb	1	0	3	4

[1] Figures refer only to number of "umbo" larvæ collected during three tidal cycles.

One thing the table clearly shows is the general scarcity of swimming oyster larvæ in this small harbor, where later many hundred thousands were found attached as spat. It can be seen that the vertical distribution of the larvæ during the low-water period as a whole was comparatively uniform, and approximately the same number was found in each sample taken from the surface to the bottom. However, upon further examination of each stage of this period, a noticeable variation in the distribution according to tidal movement was found at the time the sample was taken. On the last of ebb tide the larvæ were found to be most abundant in the bottom and mid-zone samples; at low slack water there was practically no difference in the numbers of larvæ at each depth; while in the first of flood stage the larvæ were most abundant in the surface samples. During the intermediate period only a few larvæ were found, and these were chiefly small larvæ that occurred most frequently in the bottom samples. In the samples taken during the high-water period the larvæ were also much less abundant than at low water and occurred mostly in the bottom and middle zone. The results obtained from this series of plankton collections are presented graphically in Figure 31, which shows the distribution and abundance of the oyster larvæ in relation to the height and stage of the tide.

If we classify all the plankton collections made in the harbor in 1925 and 1926 according to the stage of tide, and include also the straight-hinge larvæ, we find that the distribution of the larvæ is similar to that shown in the previous table. In the collections as a whole the straight-hinge larvæ were the most abundant, and, though a certain number were collected at nearly all stages of the tide and at all depths, they also were found to be most numerous during the low-water period, and their abundance in any zone was much the same as that of the older or "umbo" larvæ. One thing in Figure 31 that deserves notice is that the oyster larvæ are extremely scarce during the intermediate period or at the times when the vertical movement of the water is greatest.

By means of the second quantitative method employed the concentration of the larvæ at the level of the oyster bed—that is, 1 foot below low-water mark—was determined hourly according to the stage and height of the tide. In the following record for August 11, 12, and 13, 1926, the number of larvæ collected in each hourly sample of 200 gallons is given, together with the tidal data.

TABLE 15.—*Concentration of umbo larvæ in 200-gallon hourly samples taken at the level of the oyster bed*

Sample No.	Stage of tide	Height of tide (feet)	Number of larvæ per sample			
			Aug. 11	Aug. 12	Aug. 13	Total
1	Low water	0	65	74	81	220
2	First flood	1.0	120	91	106	317
3	Flood	2.2	8	5	11	24
4	do	3.8	0	0	0	0
5	do	5.0	0	1	1	2
6	Last flood	6.0	1	0	3	4
7	High water	6.2	4	2	5	11
8	First ebb	5.4	2	3	1	6
9	Ebb	4.0	0	0	1	1
10	do	2.8	0	2	0	2
11	do	1.6	2	3	4	9
12	Last ebb	.8	15	11	23	49
13	Low water	.4	54	45	67	166

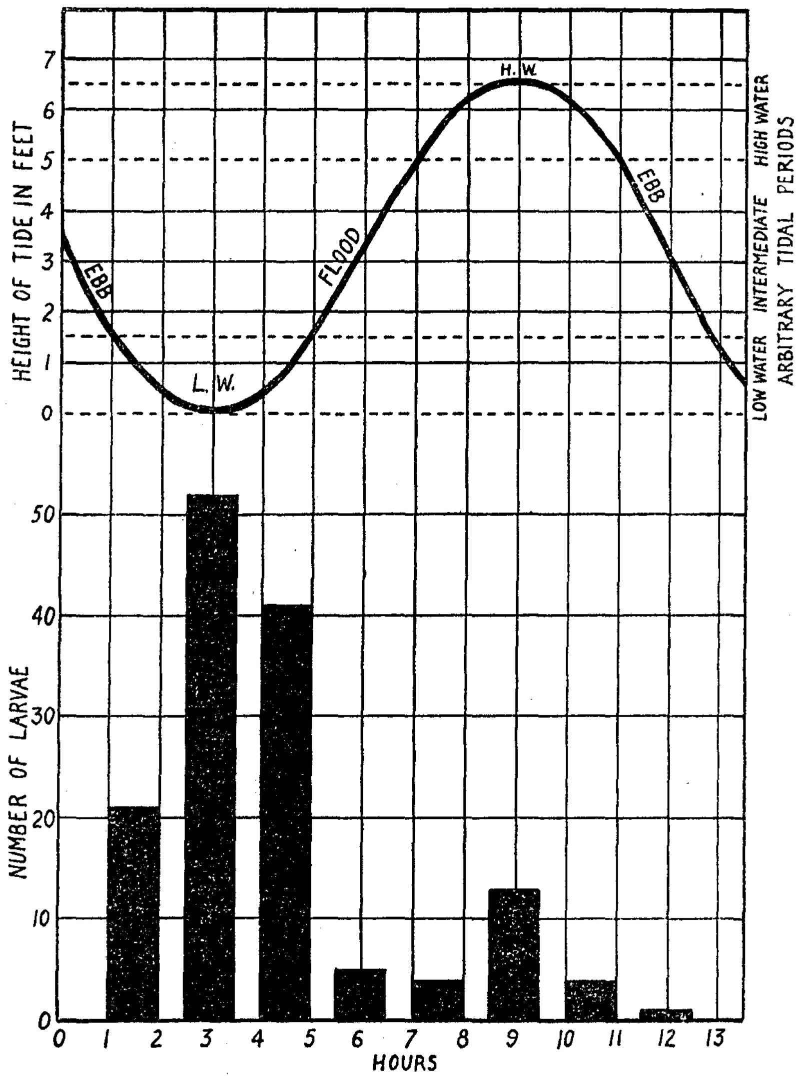

FIGURE 31.—Distribution and abundance of the oyster larvæ in relation to the stage of the tide

These collections were made a few days before heaviest setting occurred in 1926, and consequently the majority of the larvæ were full grown and were retained by the 80 and 100 mesh screens. The greatest concentration of larvæ in the hourly samples was found at the time the tide changed from low slack water to flood, when an average of 106 larvæ per 200 gallons of water were collected. This finding is quite significant in view of the fact that this is also the particular level or zone in which the heaviest setting was observed to occur. In comparing the results of both quantitative methods for the same days, we find that they are very similar and show that the largest numbers of oyster larvæ are swimming in the water in Milford Harbor during the "low-water period." In making the plankton collections from August 11 to 13, 1926, there were no unusual meteorological conditions and the range of tide was approximately 6½ feet, which is about equal to the mean daily range for this locality.

Since a general scarcity of swimming larvæ was found in the plankton collections, the question naturally arises as to where the large numbers of larvæ come from or remain that later are found attached as spat in the same areas. Two possible explanations of this phenomenon could be advanced: First, that the oyster larvæ were carried into the harbor by the flood tide from the sound, and second, that the larvæ were lying on the bottom during the greater part of the time. To investigate the first possibility, it was necessary to determine (1) the horizontal distribution of the oyster larvæ during the low-water period and (2) the occurrence and abundance of the larvæ during the flood-tide interval at Stations Nos. 4, 5, and 6, which are located outside of the harbor.

In the following table, the horizontal distribution of the larvæ during the period of low water is shown for Milford Harbor and vicinity. In this series, made on July 25, 1925, the majority of the larvæ were fully developed and were retained by the 80 and 100 screens.

TABLE 16.—*Horizontal distribution of larvæ at low water on July 25, 1925, for Milford Harbor and vicinity*

Station No.	Hour (a.m.)	Number of larvæ per 50 gallons		
		Top	Bottom	Total
6	8	16	23	39
5	8.30	2	0	2
4	8.50	18	11	29
3	9.20	35	26	61
2	9.45	27	13	40
1	10.10	8	5	13

At Station No. 6, which is located in Long Island Sound 1 mile distant from Milford Harbor, there is a large spawning bed, and here we find the larvæ fairly abundant at low water. At Station No. 5, which lies halfway between the harbor spawning bed and that at Station No. 6, the oyster larvæ were found to be virtually absent not only in the series taken at low water, but also in the samples taken at all stages of the tide during both summers. The larvæ were found in greatest abundance at Stations 2, 3, and 4 located close to the harbor spawning bed, which is the area where later the heaviest setting occurred. In their horizontal distribution we find the oyster larvæ present in greatest numbers at stations near the spawning beds and which are heavy setting areas.

The plankton collections of 1925 and 1926, which were made during flood tide at Stations 4, 5, and 6 contained, on the average, less than 2 larvæ per 50 gallons. From studies of the distribution of the larvæ at various stages of the tide in both the harbor and the Sound, it is evident that since the larvæ are absent during flood tide they could not be carried into the harbor from Long Island Sound.

The second possibility (that the larvæ were lying on the bottom the greater part of the time) was studied next by collecting thin layers of bottom at Station No. 3, near the spawning bed. The area of bottom covered by each sample was approximately 4 square feet, and the thickness of the layer that was removed was about one-fourth inch. The samples were taken during half-flood and half-ebb stages of the tide, when no larvæ could be found swimming in the water. In all, 12 bottom samples were collected, 4 of which were made in 1925 and the remainder in 1926. The bottom samples were placed in wood tanks filled with sea water and allowed to settle, after which a small stream of filtered sea water was maintained in the tank and the overflow strained through a No. 20 bolting-silk net. Oyster larvæ were obtained from all of the samples, the number per sample ranging from 15 to 147. The total number of larvæ collected in the 12 samples was 662, the average being 55 larvæ per 4 square feet of bottom. This number of larvæ on a given area of bottom is small as compared to the number of spat that were found near by on the shells and other collectors, and may be due to the fact that the samples were taken from clean and smooth areas that contained no shells or other objects that could obstruct the currents. The finding of oyster larvæ on the bottom at certain stages of the tide shows that they are not passive planktonic forms, and therefore are not subject to wide dispersal by the tides and currents. By remaining on the bottom during the greater part of the larval period, and by limiting their swimming activities to the tidal periods, when horizontal movement of the water is least, the oyster larvæ are able to remain and set on and near to the spawning bed that produced them.

One of the important questions that has presented itself in the study of the oyster is, Where does the spawn or larvæ from a bed of oysters finally attach or set? The greater production of oyster larvæ and spat in Milford Harbor following its rehabilitation has shown definitely, during the past three years, that oyster larvæ are not distributed far from the spawning bed by the currents, the predominating drift of which is out of the harbor. The final distribution of the larvæ can be determined easily by studying the relationship of setting areas to spawning bed. It has been found that the majority of the larvæ set within a radius of 300 yards from the center of the spawning bed and that the greatest number of spat per square inch or per shell is to be found on the bed within a radius of 100 yards. As indicated by setting, the larvæ are distributed both above and below the spawning bed and attach in greater numbers on the areas that are below or in the direction of the Sound. Though the intensity of setting varies from year to year, the distribution of the larvæ was found always to have this same relation each year to the spawning bed.

The occurrence and distribution of the oyster larvæ in Milford Harbor was entirely different from that found in Great South Bay, Long Island, by Churchill and Gutsell (1920 and 1921; unpublished reports) and by Nelson (1922) in Barnegat

Bay, N. J. In these bodies of water, which are quite similar, they found that oyster larvæ are abundant and actively swimming at all stages of the tide and are about evenly distributed from the surface to the bottom during the entire larval period. In order to determine the possible cause for this difference, a comparison was made of the physical conditions in each locality. Various factors, such as temperature, salinity, and hydrogen-ion concentration, were found to vary slightly but gave no indications of being controlling factors. The chief difference appeared in the tidal range and the velocity of the tidal currents in each body of water. In both Great South and Barnegat Bays the mean range of tide is approximately 1 foot and the tidal currents are very weak, while at Milford the mean range is 6.6 feet and the tidal currents attain considerable velocity, as shown previously. Since the oyster larvæ were found to be most abundant in the harbor during slack-water periods, it is probable that the current velocity is an important controlling factor. To test this, a few experiments were made during the past summer, in which the swimming movements of the larvæ were observed in relation to the current. For this purpose, an elliptical wood tank of 1,000 gallons capacity, in which larvæ were being reared, was employed, and tests were made as to the presence of the larvæ when the water stood or was in circulation. The velocity of the current created in the tank was 0.5 foot per second at the surface and 0.3 foot on the bottom. The average results obtained in four experiments are given in the following table:

TABLE 17.—*Abundance of oyster larvæ in a tank when the water is standing or in circulation*

Test	Condition of water	Number of larvæ per 200 gallons	
		Surface	2 inches above bottom
1	Standing	114	320
2	Circulating	2	3
3	Standing	154	268
4	Circulating	0	2

Additional tests were made at various points in the tank during circulation to see if the larvæ had collected in eddies or in the center, but none could be found at any place except on the bottom of the tank. The results of these experiments indicate that oyster larvæ cease swimming and settle to the bottom in currents having a velocity of approximately 0.5 foot per second. In comparing this with conditions in the harbor, we find that the larvæ were most abundant in the slack-water periods, especially at low water, when the current velocity ranged from 0 to 0.6 foot per second. When the velocity of the current exceeded this figure, the larvæ were absent from the water and were found on the bottom. The correlation between the distribution and abundance of the larvæ and the current velocity enables us to understand how the natural development and growth of the oyster beds has been possible in many harbors and estuaries where the tidal movement and river drainage would soon carry away free-swimming organisms.

In many coastal regions we find prolific oyster beds in swift running rivers that empty directly into the ocean and have currents that are many times stronger than those in Milford Harbor. The drift of the water in these streams is decidedly seaward, and the fact that under such conditions the oyster larvæ remain and set there strongly indicates that they are not actively swimming at all times. The experiments with drift bottles and the current measurements in Milford Harbor (mentioned on pp. 452 to 455) have shown that the horizontal movement of the water during ebb was much greater than during the flood, and that floating objects carried out of the harbor by the ebb current never were returned by the flood. A similar excess of ebb over flood in tidal movement can be found in nearly all of the bays and rivers emptying into Long Island Sound, and these are the very places where in the past the most prolific natural beds were found to exist.

One of the theories advanced by the oystermen to explain the continued failure of setting in Long Island Sound is that the inshore and harbor areas supply larvæ and spat for the deep-water beds in the Sound; and since the depletion of these inshore areas, oyster setting in the Sound has been a failure. Such a theory is contradicted by (1) the location of the natural beds, as shown in Figure 2; (2) the general set of 1925, when there were very few oysters on the inshore areas; and (3) the distribution of the oyster larvæ and setting in Milford Harbor in relation to the spawning bed.

In recent years, when oysters were plentiful on the natural beds, setting oftentimes failed on the leased bottoms lying outside of them in the Sound. The fact that during the past centuries the natural beds were not extended into the deeper waters of the Sound strongly indicates that oyster larvæ were not distributed freely by the currents over these areas. In 1925, oysters in sufficient quantity to produce the set that was obtained could be found only on the planted beds in the Sound, and the production of a greater number of larvæ by these oysters is the only logical explanation that can be given for successful setting during that year.

In many cases the failure of setting has been attributed to a mortality of larvæ as a result of sudden changes in temperature or salinity and to heavy rainstorms. In the studies of physical conditions in Milford Harbor during the larval period it has been found that many changes in temperature of 5 to 11.5 degrees in 24 hours and in salinity from 5 to 25 per mille produced no noticeable decrease in the numbers of larvæ present in the water. During the larval period in 1925 and in 1927 the precipitation was several inches above normal, and a tremendous amount of fresh water was discharged into Milford Harbor. The changes in salinity and the increased velocity of the ebb current following these storms apparently did not kill the larvæ or carry them out of the harbor. These studies show that oyster larvæ can withstand extreme changes in temperature, salinity, and hydrogen-ion concentration of the water and are not widely distributed by the tides and currents.

SETTING

A most important and significant period in the life history of the oyster is that during which the larva sets or attaches itself to some clean, firm surface, such as shells or stones. The act of setting was observed many times by the author, and it was possible to view this interesting process from several angles by causing the larvæ to attach themselves to glass slides. To accomplish this, the fully developed larva releases a fine, threadlike byssus, or anchor, which adheres to the first suitable surface with which it is brought in contact. The larva then ceases swimming and crawls over the surface by means of its long muscular foot, at the same time laying down the byssus behind it. After crawling about for a short time, the larva comes to a standstill, ejects a quantity of cement on its left side, and quickly brings the lower or left valve into contact with the cement-covered surface. The foot is used in bringing the shell in contact with the substratum and holds it in position for about one minute. This short interval of time is all that is necessary for complete hardening of the cement and setting of the oyster larva. Immediately following fixation, a metamorphosis occurs, and the larva develops into a spat with organs similar in structure to those of the adult oyster. At this time the newly formed spat is of the same size as the fully developed larva and measures 0.33 of a millimeter, or approximately one seventy-fifth of an inch through its greatest diameter. In shape it closely resembles a hard clam and has an amber-colored, irridescent shell, near the center of which can be seen a small, deeply pigmented spot. The spat grows rapidly and in one week is over five times its original length and in two weeks over twenty times, when it reaches a length of about 7 millimeters, or one-fourth inch. Spat of this size can easily be seen on the shells and other collectors and were the smallest to be counted in the field observations with regard to the number attached on a given area of surface.

In the studies of the distribution of setting, various types of spat collectors were used, such as tiles, brush, tar paper, and containers filled with oyster, clam, scallop, and mussel shells. The collectors were arranged so as to cover the entire zone from the bottom of the channel to high-water mark, a vertical distance of approximately 17 feet, of which the upper 5 to 9 feet are exposed by the tides. In addition, four ropes, to which tiles were attached, were suspended from an oyster float anchored near the beds.

Setting in Milford Harbor has been observed to occur from July 20 to September 1, but is generally most intensive during August, the peak occurring about the middle of the month. It was found that setting was not a continuous process, as there occurred definite periods of setting that followed spawning by about two weeks. The first set that occurs is early and extremely light and is followed by a heavy and final set about 8 or 10 days later. For example, in 1925 there were 10 to 15 spat per shell at Station 3 in the light set and from 150 to 250 spat per shell in the heavy set. An examination of the shell samples taken up daily showed that the majority of the larvæ from a single spawning became attached within a day or two of each other. In 1926 the heavy set occurred on August 16, which is representative of the average time of setting for this region. In 1925 spawning and setting occurred two weeks earlier than usual, and the heavy set was observed on July 29.

The number of spat produced in the harbor each year varied considerably, though the size of the spawning bed was virtually the same in each instance. It was found that the intensity of setting could be clearly correlated with the quantity of spawn in the oysters and the early water temperatures. In 1925, when the temperature was above normal and the oysters contained a large amount of spawn, setting was heaviest, and an average of 15,000 spat per bushel of shells was collected. In 1926 and 1927 we had the other extreme—that is, water temperatures below normal and a small amount of spawn in each oyster, with the result that the average number of spat collected per bushel was only 2,000 and 2,500, respectively. Such annual variations in the production of seed on both natural and cultivated oyster beds have long been observed and are largely the result of the annual and monthly fluctuations in the physical conditions that have been discussed previously.

DISTRIBUTION OF SET

On a given area of bottom the setting was found to be distributed unevenly and varied in intensity according to the distance from the spawning bed and the depth of water. In the harbor the set was found to occur on such areas as are covered with water when the tide is 2 feet above mean low water mark, with the exception of a small portion above Station 1, where setting occurs rarely because of the discharge of fresh water. In 1925 a set of commercial value was found principally within a radius of 300 yards from the spawning bed, the number of spat ranging from 5 or 6 spat per shell on the outside edge to 200 and 300 per shell in the central portion. The spat were most abundant on shells planted over the spawning bed and within approximately 100 yards of its center. The concentration of spat at the 100-yard circle averaged 50 per shell. Though setting occurred at virtually the same distance upstream, or above the bed, as it did below, it was found to be of slightly greater intensity in the areas lying below or toward Long Island Sound. The horizontal distribution of the set in relation to the spawning bed clearly shows how close the oyster larvæ remain and attach to the place where they were produced. No noticeable difference in the distribution of set from the spawning bed could be found in the last three years. These facts make possible the development of special methods of oyster-seed collection on the same areas where the heaviest setting is found to occur.

The variations in intensity of setting according to depth, or, in other words, the vertical distribution of spat, has been found to be quite peculiar in Connecticut waters. Setting occurs in a zone extending from the bottom of the channel to a point 2 feet above mean low-water mark, while from above this level to high-water mark, a distance of about 5 feet, no setting takes place. The vertical range of setting found in other bodies of water is quite different, as shown in Figure 32. In Great South Bay, Long Island, setting occurs from the bottom to nearly high-water mark, while in South Carolina and Georgia the set is found chiefly between low and high water marks and not below low-water mark. Since the velocity of the tidal current was found to be an important controlling factor in the distribution and occurrence of the oyster larvæ, it appeared likely that it might also exert considerable influence on the distribution of setting. In the studies of the relationship between current velocity and setting it was found that in Milford Harbor the larvæ began to attach at low slack water and continued to do so during the first two hours' run of flood tide until the current had developed a velocity of one-third foot per second, or 20 feet per minute. This was determined not only by plankton collections of fully developed larvæ but especially by observations as to the position of the larvæ on the collectors in respect to the stage of tide and the velocity and direction of currents. The portion of the collectors covered at low water, when there was no current, was found to be covered equally with spat on all sides, while above this level spat occurred chiefly on the lee side or that which was protected from the force of the flood current. Shells that were put out at low water and taken up after two hours' run of flood tide were the only ones on which newly attached spat had collected.

In Great South Bay, Long Island, the zone of setting can be correlated with the vertical distribution of the oyster larvæ and the current. Here there is virtually no current, and the spat are found attached from the surface to the bottom, which corresponds to the distribution of the larvæ. Tidal conditions similar to South Bay were found in Holly Pond on the Connecticut shore, where the water was impounded for hydraulic power by means of a dam. There are insignificant tidal currents in the pond, as it receives water from Long Island Sound only on the very last of flood tide before high water. An examination of the pond showed that seed oysters were attached in a zone extending from the bottom of the pond to within 1 foot of high-water mark, while just outside and below the dam the vertical distribution of spat was entirely different and the same as found at Milford. In this instance the chief difference in the physical conditions above and below the dam was the velocity of the tidal current, which undoubtedly is an important factor in controlling the zone of setting in both places.

In South Carolina and Georgia waters, where setting occurs between the tide marks, it may also be interpreted on the basis of current velocity, though no actual measurements in this region have yet been made. According to Marmer (1926), the tidal current in the mouths of most bays and rivers is different than in Long Island Sound, and slack water occurs when the tide is about halfway between low and high water marks. This means that in these coastal rivers the current will have zero velocity at about half tide level in the lower portions of the streams. In examining the piling and tidal flats at many points in South Carolina it was found that oyster setting was heaviest about halfway between tide marks and gradually decreased in intensity in the zones a few feet above or below this level in accordance with the increase in velocity of the currents. An interesting observation in this connection was made near Beaufort, S. C., where a bridge was being constructed and cofferdams had been used in laying the piers. An examination was made of several of the steel plates used in mid-channel in the Beaufort River operations and which had been taken up and placed on the wharf. On the outer surface of the plates, the spat were found attached between high and low water marks, a distance of about 6 feet, the distribution being the same as is found on the piling along the shore. However, on the inner surface, the attachment of the spat was quite different and was found to extend from the mud line, or bottom of the channel, nearly to high-water mark, a difference of approximately 16 feet. The extreme difference in the vertical distribution of setting on the outside and inside of the cofferdam apparently was due to the fact that there were no currents within the dam and consequently the larvæ were able to attach there from virtually the surface to the bottom.

Although the vertical range of setting in Milford Harbor is several feet, the intensity or number of spat per square inch at all points or levels is not the same. The relative intensity of setting throughout the zone of attachment is shown in three different localities in Figure 32. In Milford Harbor the actual number of spat attached per square inch at all levels was determined for the set of 1925. The setting was found to be most intensive in a narrow strip extending approximately from a point 1 foot above the level of low-water mark to 1 foot below it. Here the concentration of spat averaged 25 per square inch of surface. Above this strip, setting gradually decreased in intensity until at a level 2 feet above low-water mark scarcely one spat was found per square inch. From a point 1 foot below low-water mark to the bottom of the channel setting was comparatively light, averaging about one spat per square inch. Directly on the bottom setting was slightly heavier, and an

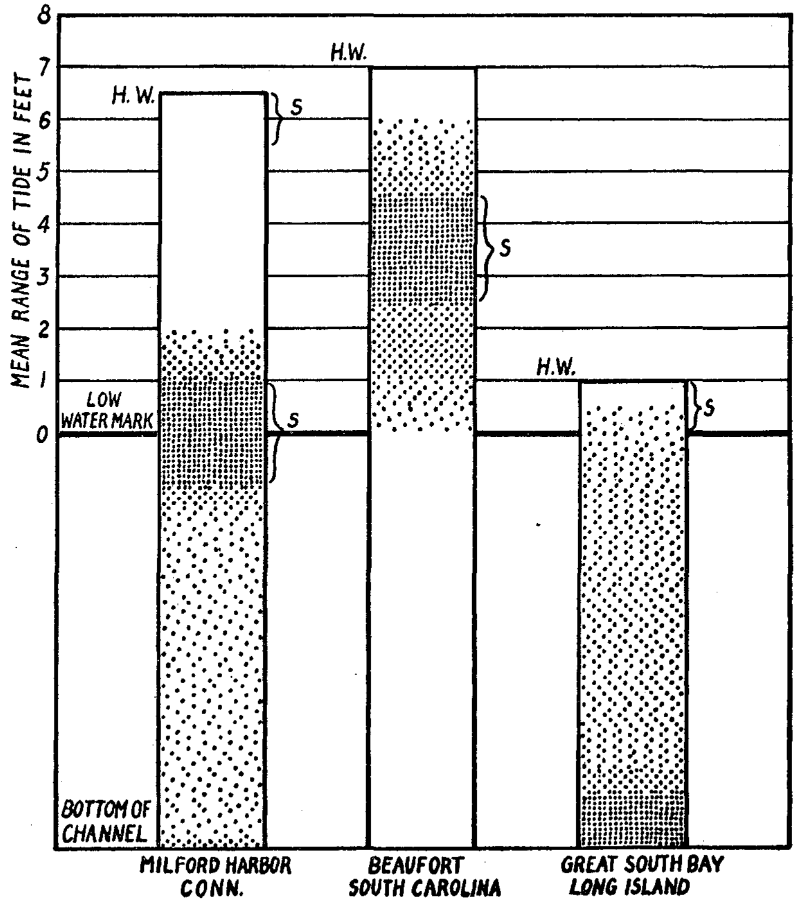

FIGURE 32.—Vertical distribution and intensity of setting of oyster spat in relation to range of tide. H. W.=high-water mark. S.=height of tide when slack water occurs

average concentration of 3 spat per square inch was found. The variations in intensity of setting at different levels can be correlated closely with the distribution and occurrence of the larvæ and the velocity of the tidal currents. During low slack water the zone in which the larvæ are most abundant and where the heaviest setting of spat takes place is that in which the velocity of the current is least, or practically zero. The reason that setting is not of equal intensity from low-water mark to the bottom of the channel can be accounted for by the fact that at low slack water, when setting occurs, the zone of least velocity is at the surface only and does not extend to the bottom. This is due to the underrun of flood tide along the bottom while the surface strata of less saline water is still on the ebb or at a standstill.

It was found that at low water in Milford Harbor the current velocity increases from zero at the surface to 24 feet per minute on the bottom, where the tide has already been running flood for some time. Under such conditions it is apparent that at any point from the surface layer to the bottom the current will be slack or of low velocity for a very short interval. Consequently, the oyster larvæ in this zone have a limited time in which to attach, and setting here is of a much lower concentration on a given area than is found at low-water mark when the slack-water interval is much longer. With the change of tide from ebb to flood, it was observed that as the water level rose from low-water mark to approximately 1 foot above it, there was virtually no current at the surface, while during the next rise of 1 foot the current increased rapidly to one-third foot per second. This sudden increase in the horizontal movement of the water as it rises from 1 to 2 feet above low-water mark is due to the water leaving the channel and spreading rapidly over the tidal flats. In the zone from low water to 1 foot above, setting is heavy; while at from 1 to 2 feet above, the number of spat per square inch decreases gradually until, at the 2-foot level, very few are found. The upper limit of setting in Milford Harbor is determined by the height of the tide when the surface current has attained a velocity of one-third foot per second after the period of low slack water.

Since the current velocity at any level varies from day to day with the changes in the range of tide, it is to be expected that sets occurring at different times would have a different upper limit. This actually was found to be the case with the two sets of 1925 and was the first clue that led to the studies of the relationship between current and setting. For the light set on July 20, 1925, the upper limit of setting on the glazed-tile collectors was 1 foot above mean low-water mark, while with the heavy set on July 29 it was 2 feet above. The range of tide in the first instance was 7 feet, while at the time of heavy set it was 6 feet. We know that current velocity increases with range of tide, and consequently the current on July 20 was stronger at the 1 or 2 foot level than it was on July 29. Under these conditions the limit of setting naturally would be lower for the light set, when the currents were noticeably stronger, and would prevent attachment of the larvæ above the 1-foot level. The tile collectors, under the same conditions, also show clearly the relative intensity of the two sets in 1925. The surface of the tiles was approximately 1,000 square inches, and the average number of spat collected per tile was 1,500 from the first set and 4,000 from the second or heaviest set. The setting on the tiles was not uniform, of course, but decreased in intensity from the bottom to the upper setting limit.

Observations were made, also, in regard to the distribution of the spat on the collectors in relation to the direction of the tidal currents when setting took place. At low water and on the first of flood tide the horizontal current movement is very weak, so that the current meter was useless for determining its direction or velocity. For this purpose a simple device was used, which consisted of a hollow brass rod ¼ inch in diameter, to which pieces of fine white thread 1 foot long were tied at intervals of 3 inches. By setting up the rod near the collectors the direction of the current could be seen easily at depths up to 3 or 4 feet. The distribution of setting on the collectors was found to depend largely on their shape and the position in which they were placed on the tidal flats in relation to the direction of the flood current. The heaviest setting was found near the bottom and on the lee side of the collectors, presumably because of the eddies created by them. The setting on the brush that was planted on the tidal flats is a good example of the effect of the current on attachment of the larvæ. For a distance of about 3 inches above the bottom the spat were found on all sides of the main branches and were most numerous on the lee side. From above the 3-inch level to about the 1-foot level the majority of spat were distributed only on the lee side and decreased gradually in numbers from the bottom upward. Branches having the greatest diameter caught the most spat, while small twigs at the same level caught virtually none. Further indication that current velocity is an important factor controlling setting was found from a comparison of the distribution of spat in wire baskets filled with oyster shells with that on the brush. The baskets were set out next to the brush and were found to have received a much heavier set. The spat were found attached in the baskets up to 2 feet above the bottom, whereas on the brush setting stopped 1 foot above the bottom. The intensity of setting in the baskets varied from 150 to 200 spat per shell in the bottom layer to an average of 25 per shell at the top of the basket. The differences in the intensity and upper limit of setting in the baskets as compared with the brush undoubtedly is due to the type or shape of each collector. The baskets were a greater obstruction to the current, and by decreasing its velocity they facilitated the setting of a larger number of larvæ.

In summarizing the studies of the time and distribution of oyster setting in Milford Harbor, it has been found that—

1. Heaviest setting occurs in the surface layer during the period of low slack water, which is the zone in which the oyster larvæ were found to be most abundant.

2. Setting continues as the tide begins to run flood, gradually becoming less intense as the velocity of the current increases, and finally ceasing altogether when the current attains a velocity of 10 centimeters, or one-third foot, per second.

3. The intensity and vertical distribution of setting varies according to the current velocity at the times when oyster larvæ that are ready to set are found swimming in the water.

4. The distribution of spat on various types of collectors depends upon their shape and especially on the position in which they are placed in relation to low-water mark and the direction of the flood current.

5. The upper limit of setting varies according to tidal conditions when each set occurs. The range of tide, level of low slack water, and rate of increase in current velocity can be correlated with the intensity of setting and changes in the upper setting limit.

By comparing the tidal conditions in various oyster regions it has been found that the zones in which the oysters are attached and the distribution of the natural beds can be correlated with the velocity of the currents and the distribution of the oyster larvæ, the heaviest setting occurring at the levels where the larvæ are abundant when the current reaches its minimum velocity.

PREDICTING THE INTENSITY AND TIME OF OYSTER SETTING[2]

The production of seed oysters on both the natural and cultivated beds in Connecticut has fluctuated tremendously from year to year; for example, from over 1,000,000 bushels in 1925 to virtually none in 1926 and 1927.

The present investigation has shown that the physical conditions in 1925 were decidedly different than in 1926 and could be correlated with the quantity and ripeness of the spawn in the oysters, the time of spawning and setting, and the intensity of setting or quantity of seed oysters that were produced each year.

The data on the various factors have been presented, analyzed, and discussed as to their effect on the oyster and oyster larvæ and the environmental conditions over the oyster beds. Of the many factors involved, water temperature has been found to be the most important in controlling the development and ripening of the gonads and in determining the time of spawning and setting. The studies have shown that the success or failure of setting and its intensity depend largely upon the departures of temperature from normal. As is shown in Figure 28, during the past six years setting in Long Island Sound has been successful when the temperature was above normal and has failed when it was below, for the period April to August. Another important factor is the relationship between the range of tide and the increase in water temperature to 20° C. and above, which is necessary to induce spawning of the oyster.

The present investigation would not be complete without a discussion of the economic and practical value of the results that have been obtained. The most important application that can be made is in predicting the intensity and time of oyster setting in Connecticut waters. A method or plan of procedure has been developed for the purpose of determining or predicting, one month in advance, (1) the relative intensity of setting that will occur and (2) the time when spawning and setting will take place. The fundamental principle of the method is a comparison of the records of the present season with those of the preceding years for which the time of spawning and yield of seed oysters is known. The predictions can be made from about the 1st to the 10th of July of each year after careful consideration has been given to the following conditions:

1. The quantity of adult oysters on the beds.
2. Water temperature from April to July.
3. Quantity and degree of ripeness of the spawn.
4. The range of tide for July and August, as shown in the tide tables.

The first condition obviously is important and can be determined without difficulty from the planting records of the oyster-growing concerns or by examination of the oyster bottoms. This factor is of great significance because it is multiplied by the quantity of spawn per oyster and gives the approximate total quantity of spawn that can be discharged into the water.

The second condition, water temperature, preferably should be determined by a thermograph, although an approximate estimation can be made as to its departure

[2] Predictions in regard to oyster spawning and setting in Connecticut waters were made on July 1, 1928, using as a basis the conditions herein described. The light general set that was predicted to occur on Aug. 11 did take place at that time and in the quantity anticipated. On the beds off Stratford Point and Bridgeport the set on Aug. 11 averaged 10 spat per shell, while off New Haven an average of 12 spat per shell was found on Aug. 15.

from normal by reference to the air temperatures at near-by stations. If water temperatures for this period are found to be above normal, the outlook for setting is favorable; when below, it is unfavorable. The mean daily water temperature on the bottom or the temperature at the times of high and low water must be determined for a few days around the 1st of July, as it has direct bearing on the attainment of a spawning temperature later.

The third condition, quantity of spawn per oyster and its degree of ripeness, can be determined by the methods discussed previously on page 474. These factors not only reflect water temperatures that occurred previously, but will show how great a quantity of spawn can be discharged by each oyster when water temperatures are suitable. Successful spawning can be expected only at a temperature of 20° C. or above, when the gonads are ripe and when a sufficient amount of spawn is released to insure fertilization.

The final analysis of the first three conditions mentioned will indicate whether the total amount of spawn available is large or small and whether it is ripe enough to be released by the oysters. It will indicate also whether a light, medium, or heavy set can be expected, as this has been found to depend largely upon the combination of the first three conditions.

The fourth condition, range of tide, should be considered for the purpose of determining the time of spawning and setting. The relation of this factor to water temperature and spawning, as discussed previously on page 480, shows us that during the full-moon tidal period, in July or the first part of August, we may expect a rise in water temperature of approximately 10° C. as a result of the warming of the water on a greater area of tidal flats. The time of full-moon tides and the daily range can be found in the tide tables issued by the United States Coast and Geodetic Survey. During this period the date on which the water will reach 20° C. or more certainly depends upon weather conditions and the temperature of the water at the beginning of the period. The records for 1925 and 1926 show that when the temperature at the beginning of the full-moon tidal period was 16° to 18° C., spawning occurred about 10 days later in the harbor and inshore areas and about 15 days later, or at the end of this period, in Long Island Sound. In calculating the time of spawning, the ripeness of the oysters and early July water temperatures must be taken into consideration. The time of setting depends, of course, on spawning and will follow it by an interval of approximately two weeks.

In the following table a comparison is given of the four conditions as they were observed in Milford Harbor on July 1 in 1925, 1926, and 1927, together with the results obtained each year in regard to time of spawning and setting and intensity of setting.

TABLE 18.—*Comparison of conditions in Milford Harbor on July 1 with intensity and time of setting in 1925, 1926, and 1927*

Conditions observed	1925	1926	1927
Water temperature variations (Apr. 1 to July 1)	+3.5° C. above normal	−3.3° C. below normal	−1.7° C. below normal.
Water temperature on July 1 (at Station 2)	15.8° C	13.5° C	14° C.
Quantity of spawn per oyster	Large	Small	Small.
Condition of gonads	Ripe	Unripe	Unripe.
Quantity of adult oysters	700 bushels	1,000 bushels	1,000 bushels.
Greatest range of tide	July 7	July 26	July 17.
Time of spawning	July 13	Aug. 1	July 14.
Time of setting	July 29	Aug. 16	Aug. 8.
Intensity of setting (spat per bushel of shells)	15,000	2,000	2,450.

Milford Harbor is a natural oyster region, and virtually every year there is a set of oysters that varies in intensity in accordance with the conditions shown in the table. In Long Island Sound, oyster setting is less regular, and here there was a similar fluctuation from a good set in 1925 to virtually none in 1926 and 1927.

Though the method is new and far from being a statistical computation as to the probability of the time of spawning and intensity of setting, it has proved to be reliable after a trial of three years, and the results obtained strongly indicate that it is based on the predominating factors that control oyster propagation. By accumulating a greater number of data of this sort the method can be placed on a statistical basis, definite values can be given to each variable, and more accurate predictions can be made as to the yield of seed oysters per year.

PRACTICAL APPLICATION OF THE METHOD

Advance knowledge of the time and intensity of setting of oysters is of value from a practical standpoint, because it can be utilized in controlling shell-planting operations so as to obtain the maximum yield of seed oysters per year. On the results obtained on July 1, deductions can be made as to (1) the quantity of shells or cultch to be planted so as to take full advantage of the years of good set; (2) how rapidly shell-planting operations must be carried on in order that they may be completed before setting occurs; and (3) the areas or beds that are most favorable for obtaining a set under the existing conditions.

There is no better way to increase the yield of seed oysters during favorable years than by increasing the amount of cultch, especially on the best setting areas. An acre of bottom that produces 500 to 1,000 bushels of set, averaging 25, 50, or more spat per shell, has been poorly utilized, because its production could easily have been increased many times by additional shell plantings. By obtaining the maximum yield during the best setting years the industry is benefited not only by having seed to grow for the market but by having, in the coming summers, a good supply of oysters for the production of spawn and future sets.

This method of predicting the intensity of oyster setting can be used in the future in conjunction with the improved methods of seed collection that have been developed by the bureau and will be described in a later report.

SUMMARY

1. The physical conditions in Milford Harbor and vicinity during the summers of 1925 and 1926 have been discussed with special reference to the more important factors—temperature, salinity, hydrogen-ion concentration, tides, and currents.

2. The most important factor, water temperature, varies according to climatological conditions and is affected most by them when the daily range of tide is greatest.

3. The water temperatures from April to July were found to have a pronounced effect upon the quantity and ripeness of spawn in the oysters, while the temperatures in July and August were found to be important in affecting the time of spawning.

4. Annual fluctuations in the intensity of setting and the production of seed oysters in Milford Harbor and Long Island Sound can be correlated with water temperatures during the spring and early summer months.

5. During the past six years oyster setting in Long Island Sound has been successful when air and water temperatures were above normal and has failed when they were below normal.

6. Though some setting occurs each year in Milford Harbor, it was found that over seven times as many spat per bushel were produced in 1925, when early water temperatures were 3.5° C. above normal, than in 1926, when they were 3.3° below normal.

7. Oyster spawning occurred on different dates during each summer and was found to be dependent upon an increase in water temperature to 20° C. and above.

8. The time of spawning and the greatest increase in water temperature were found to take place during the "full-moon tidal period" in July or the first part of August. As a result of greater range of tide during this period, the water was brought to a spawning temperature by heating on a larger area of tidal flats.

9. In studying the occurrence and distribution of the oyster larvæ, over 315 plankton collections were made, which showed that the larvæ were relatively scarce in the water in proportion to the number of spat found later in the same areas.

10. The oyster larvæ were found to be most abundant at the time of low slack water and gradually disappeared as the tide began to run flood.

11. When the flood current had developed a velocity of 0.6 foot per second, virtually no larvæ could be found swimming in the water; while samples of bottom taken at the same time contained an average of 14 larvæ per square foot of surface.

12. Experiments with oyster larvæ in a tank showed that they swam while the water was at a standstill but dropped to the bottom when it was put in circulation with a current velocity of 0.3 to 0.5 foot per second.

13. The majority of oyster larvæ produced by the spawning bed in Milford Harbor were found to remain and set within 300 yards of its center. This is accomplished by the oyster larvæ remaining on the bottom during the greater part of the larval period and limiting their swimming activities to the tidal periods, when horizontal movement of the water is least.

14. The duration of the larval period was found to vary from 13 to 16 days. The average of the four periods observed during 1925 and 1926 was 15 days at a mean water temperature of 21.5° C.

15. Setting of oysters occurs at from 2 feet above low-water mark to the bottom of the channel and is of greatest intensity in a zone lying at from 1 foot above mean low-water mark to 1 foot below it.

16. Setting or attachment of the larvæ was found to take place during low slack water and continued until the flood tide had developed a velocity of 0.33 foot per second or 20 feet per minute.

17. It was found that the vertical distribution of spat and the intensity of setting in any zone could be correlated with velocity of currents and distribution of oyster larvæ.

18. As a result of the investigation of the physical conditions and the biological studies of the oyster, a method has been developed for determining or predicting, one month in advance, (1) the relative intensity of setting that will occur each year and (2) the time when spawning and setting will take place.

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