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THE DISTRIBUTION OF OXYGEN IN THE WESTERN BASIN OF THE NORTH ATLANTIC

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PREFACE

This report is based on material obtained during the following cruises of the research ship "Atlantis" into the western North Atlantic basin: Cruise 1, July and August 1931; Cruise 6, February to April 1932; Cruise 11, August and September 1932; Cruise 15, February to May 1933;[1] and on such earlier data as are available.

The preparation of this report has been guided by Professor H. B. Bigelow. Part of the reduction of the material, aided by a Scandinavian-American fellowship, 1932–1933, was done at the Geofysiske Institutt in Bergen where I had the pleasure of many consultations with Professors Helland-Hansen and Sverdrup.

[1] For publication of "Atlantis" observations see Bulletin Hydrographique pour L'Année 1932, Conseil Internat. Explor. de la Mer, 1933.

INTRODUCTION

The distribution of dissolved oxygen in the sea is controlled by a combination of its physical, chemical and biological characteristics; on the one hand, the chemical and biological activities tend to vary the content of the dissolved gas whereas, on the other, the circulatory agencies tend to redistribute the oxygen and bring about equilibrium. The fact that there is a constant consumption of dissolved oxygen in the depths and that frequent supersaturation with oxygen occurs at or near the surface of the ocean was observed on the "Challenger" expedition (Dittmar, 1884). An explanation of the cause of supersaturation of oxygen, however, was not forthcoming until 1899 when Martin Knudsen suggested that it was caused by photosynthetic activities of vegetable plankton.

The original oxygen content of ocean waters has been obtained from a thin surface layer in contact with the atmosphere and as a product of photosynthetic activity. In modern concepts of oceanography it is a generally accepted fact that the water masses of the depths of the oceans have at some time and place been at the surface where under the influence of climatic conditions they acquired distinct temperature, salinity and oxygen characteristics. The sinking of the surface layers in the so-called regions of convergence and their ultimate distribution by means of quasi-horizontal and convectional currents results in the whole of the ocean basins being filled with water which has acquired its fundamental characteristics while under the influence of atmospheric conditions.

From general knowledge of oceanic circulation, based on researches of Nansen (1912), Jacobsen (1929), Wüst (1928), etc., the water of the western basin of the North Atlantic is probably of several origins and consequently of different ages and oxygen contents. Thus, the deepest part of the whole basin, up to depths of 2000–1500 meters appears to contain water which, for the most part, originated at the surface in high North Atlantic latitudes. Lying on top of this deepest water there is, in the northern half of the region, what appears to be a mixture of it and other North Atlantic water, while in the southern half of the region there is at intermediate depths a mass of water which apparently originated at the surface in high latitudes of the South Atlantic.

REGION OF INVESTIGATION

The present discussion is confined to the offshore western basin of the North Atlantic. The region of investigation, lying west of the 40th meridian and south of the 43rd parallel of latitude, is covered by six oceanographic sections made by "Atlantis" in 1932 and 1933 together with miscellaneous stations from "Atlantis" and other earlier expeditions (fig. 1).

Section A, approximately 1000 miles long, was run from February 24 to March 4, 1932; section B, more than 2000 miles long, March 4 to March 21, 1932; section C, approximately 700 miles long, April 7 to April 13, 1932; section D, about 650 miles long, February 12 to February 19, 1933; section E, about 600 miles long, April 17 to April 22, 1932; and section F, approximately 500 miles in length, August 14 to August 21, 1932. Thus, sections A, B, and D were made in winter when surface layer temperatures should be near the annual minimum, section F in mid-summer when surface temperatures are near the maximum, while sections C and E were in early spring.

METHODS

For discussion of hydrographic work and method of collecting water samples and temperatures on board "Atlantis" see Iselin (1933). The determinations of dissolved oxygen were made by Winkler's method. The oxygen sample was drawn off and fixed as soon as the Nansen water bottles were brought on deck, and then kept water sealed until they could be acidified. After a short storage period in the dark the free iodine was titrated with 0.01 normal thiosulphate solution, the latter was standardized at the beginning and end of each series with 0.01 normal potassium dichromate. For details of Winkler's method see Harvey (1928) and Jacobsen and Knudsen (1921). For reduction of absolute to relative values the solubility tables of C. J. J. Fox (1907) were used; as no account has been taken of the vapor pressure of water a small error is introduced in this result, which, however, is of no greater magnitude than customary errors in oxygen analyses carried out at sea.

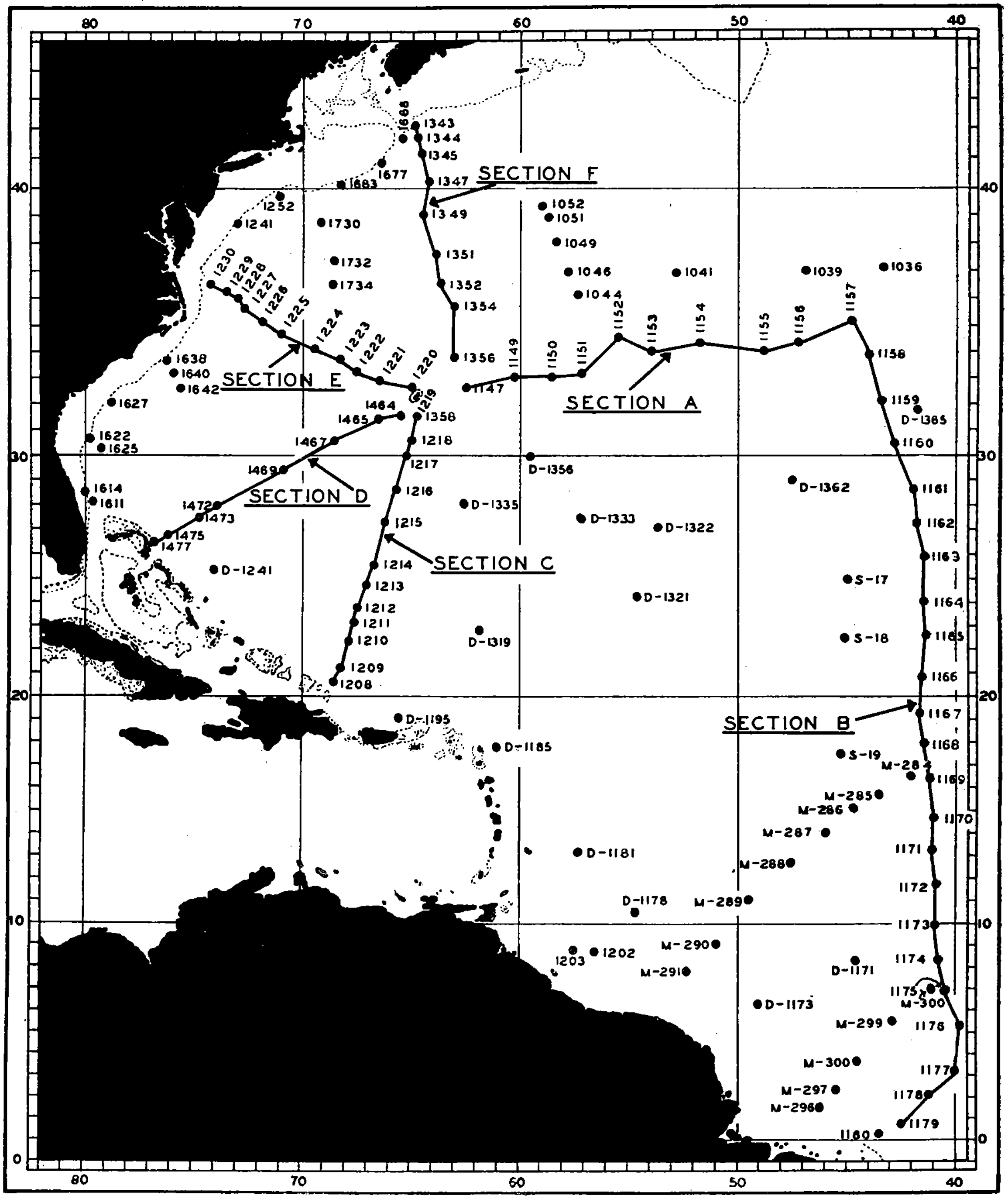

FIG. 1.—Chart of area of investigation in western North Atlantic showing locations of stations. Unlettered stations = "Atlantis" (footnote 1); D stations = "Dana" (Schmidt, 1929); M stations = "Meteor" (Wattenberg, 1933); S stations = "Deutschland" (Brennecke, 1921).

PART I

DESCRIPTIVE

VERTICAL DISTRIBUTION OF OXYGEN

Throughout the part of the North Atlantic under discussion the maximum oxygen content occurs at or close to the surface (89 to 106 per cent of total saturation, 4.49 to 5.82 cc per liter). From the surface downward the oxygen decreases to a minimum (>60 to 27 per cent of total saturation; 4.4 to 1.7 cc per liter) at intermediate depths, usually between 300 and 900 meters. With increasing depth the oxygen again increases usually to about 2000 meters (73 to 88 per cent of total saturation, 5.4 to 6.7 cc per liter) below which depth it is relatively constant.

For convenience as well as for theoretical reasons (page 71) the following detailed description of vertical distribution is made on the basis of the three oxygen layers: richest near the surface, poorest in mid depths and again rich in the underlying strata, as defined by the position of the isoline of 60 per cent relative saturation. These may be termed: "upper," "minimum" or "poor," and "underlying" or "lower" oxygen layers. In order to bring out the regional differences, conditions existing along the several sections are considered separately.

Northeastern Sargasso Sea between Bermuda and 35th Meridian ("Atlantis" Section A)

The maximum oxygen content in the surface layer ranged from 89 to 102 per cent of total saturation, 4.90 cc to 5.62 cc per liter. The minimum in intermediate depths lies usually between 700 and 800 meters (55 to >60 per cent of total saturation, 3.35 to 4.40 cc per liter). With increasing depth the oxygen again increased to about 6 cc per liter, 81 to 83 per cent of total saturation at about 2000 meters depth; below which it is in general 5.9 to 6.1 cc per liter, 78 to 80 per cent of total saturation down to the greatest depths sampled (>4000 meters; table 1; figs. 2 to 4).

TABLE I

Station	North Latitude	West Longitude	Surface Oxygen cc/liter	Surface Oxygen per cent	Minimum Oxygen depth	Minimum Oxygen cc/liter	2000 M O_2 cc/liter
1147	32°37′	62°35′	5.01	94	800	3.35	5.91
1149	32°59′	60°16′	5.11	94	800	3.45	5.95
1150	33°02′	58°37′	5.16	95	780	3.60	6.05
1151	33°11′	57°07′	5.09	94	800	4.00	6.00
1152	34°48′	55°30′	4.90	89	760	3.55	6.00
1153	34°02′	54°05′	5.08	93	840	3.70	6.18
1154	34°20′	51°45′	5.11	93	780	3.50	—
1155	34°02′	48°50′	5.67	102	720	3.90	6.05
1156	34°23′	47°11′	5.18	95	680	3.48	6.00
1157	35°10′	44°40′	5.29	96	830	4.40	5.90

Stations in section A. Minimum values 55 to >60 per cent of total saturation and 2000 meter values 80.5 to 82 per cent. Minimum and 2000 meter values scaled from station curves.

In the water between Bermuda and the 35th meridian, as indicated by section A, the upper boundary (60 per cent isoline) of the oxygen poor layer laid between 600 and 780

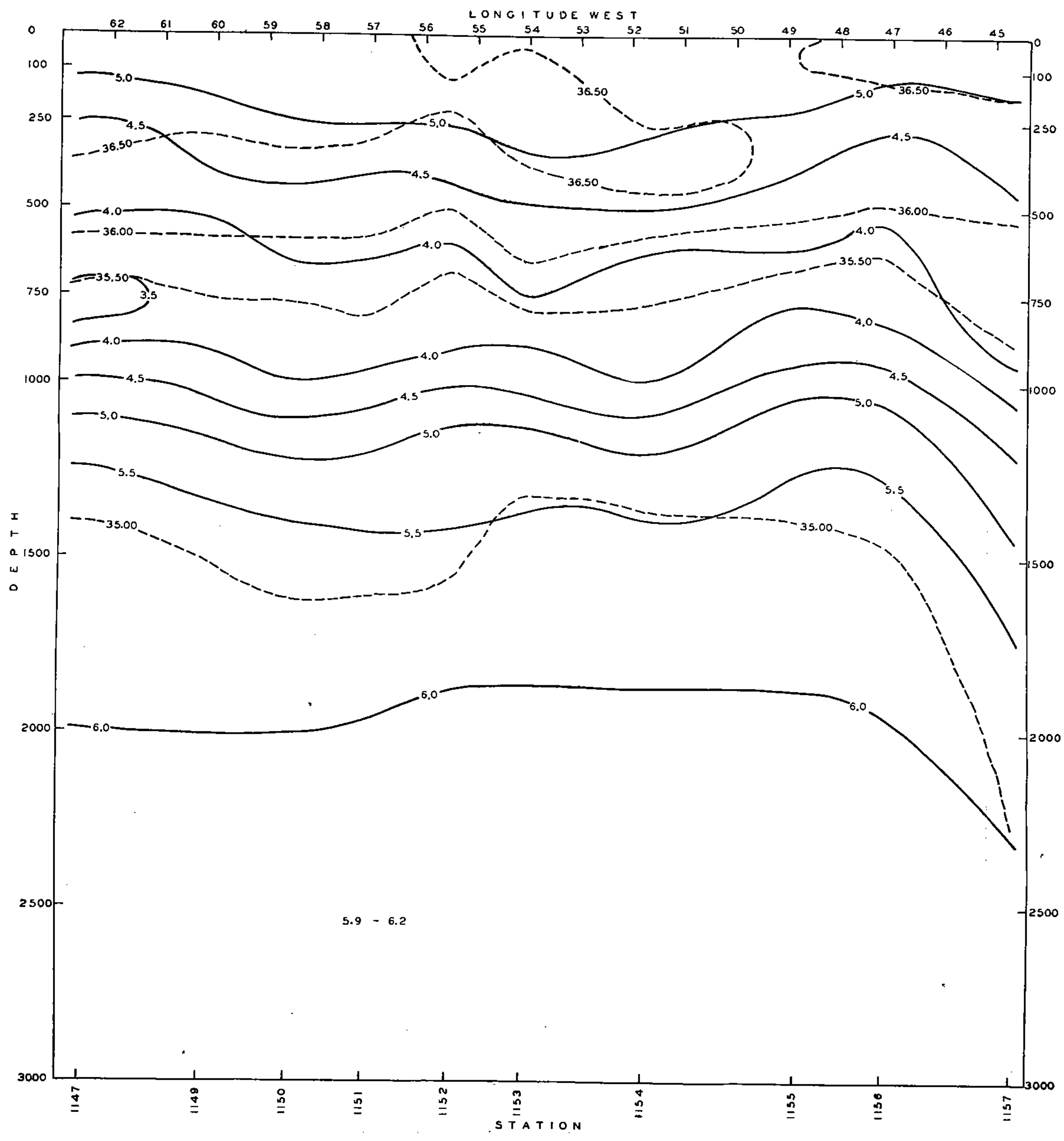

FIG. 2.—Distribution of oxygen, cc per liter, "Atlantis" section A (stations 1147–1157, longitude 62° 35′W to 44° 40′W, between latitudes 32° 37′N and 35° 10′N). February-March, 1932.

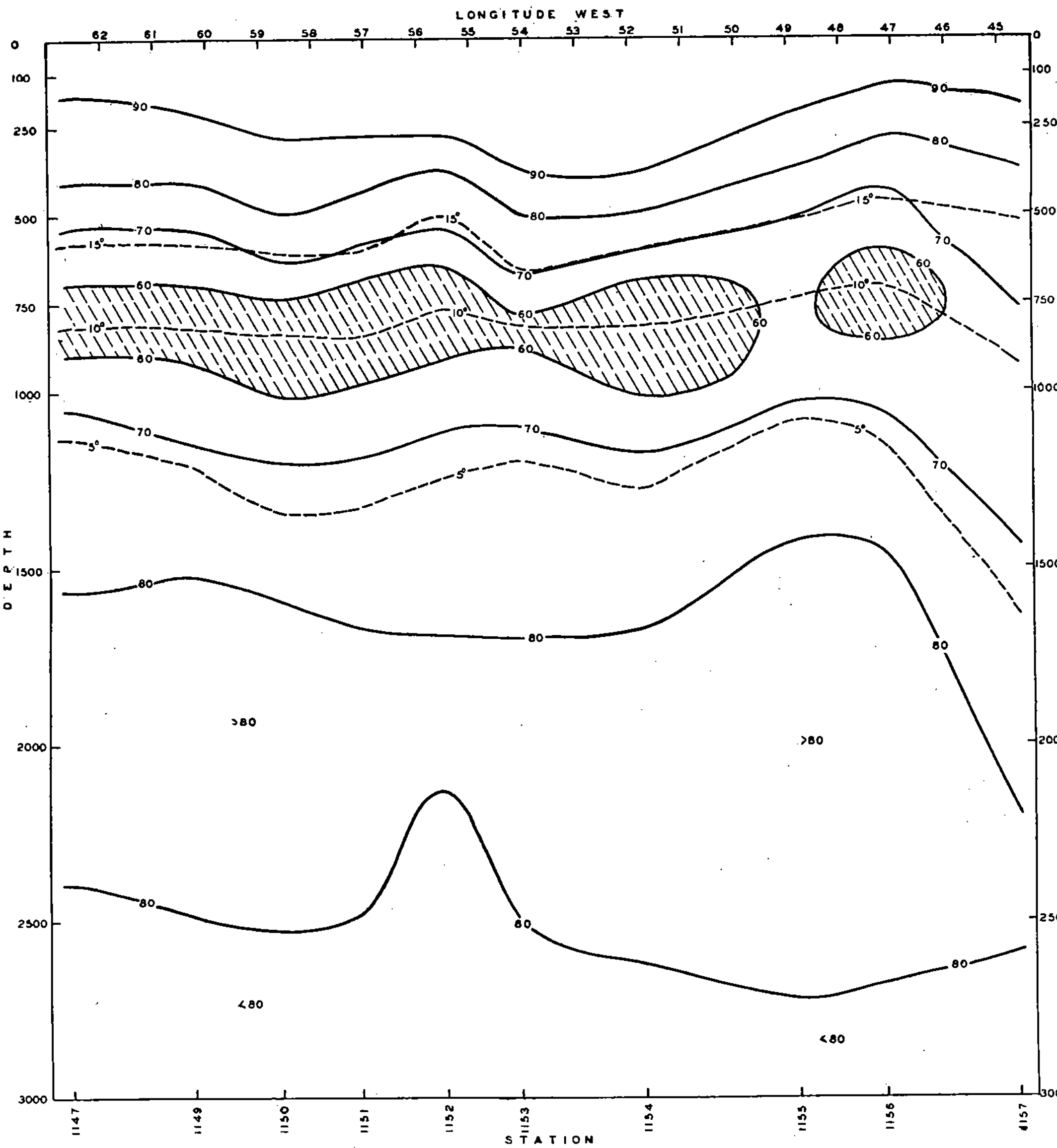

FIG. 3.—Distribution of oxygen, per cent of total saturation, "Atlantis" section A (stations 1147–1157, longitude 62° 35′W to 44° 40′W, between latitudes 32° 37′N and 35° 10′N). February-March, 1932.

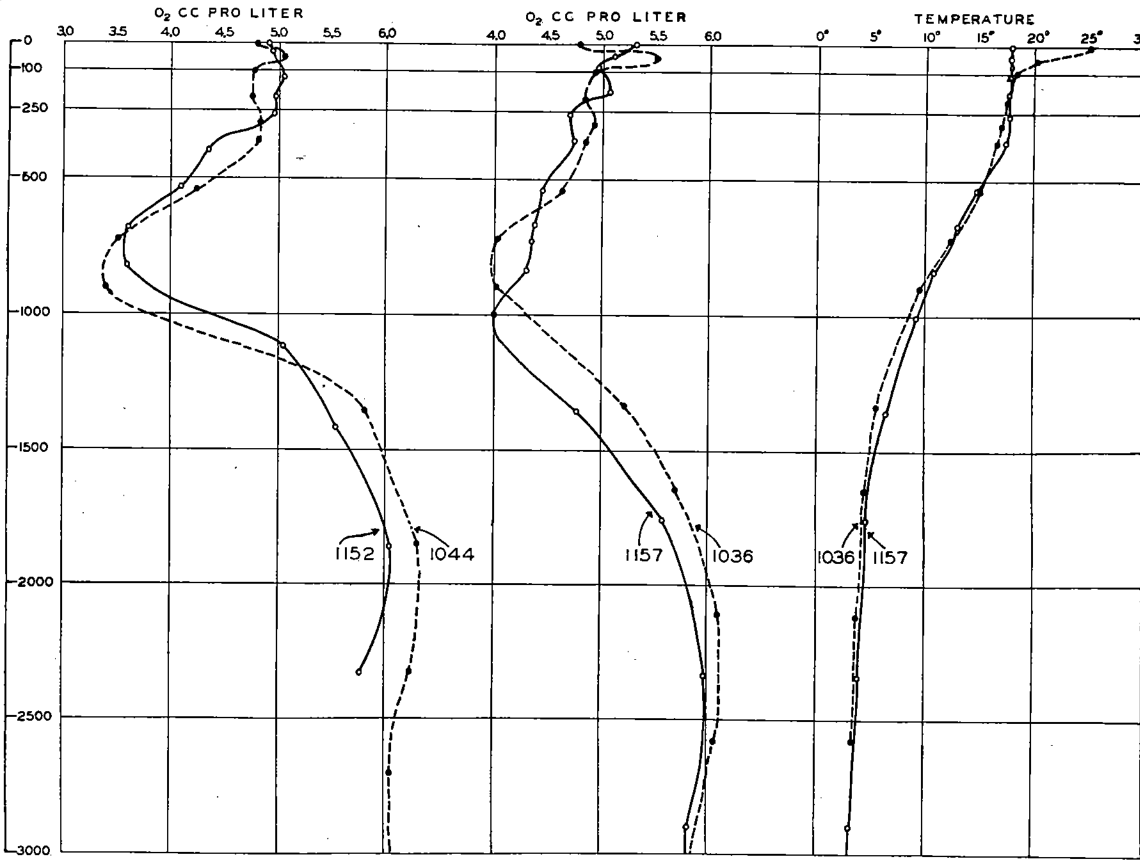

FIG. 4.—Vertical distribution of oxygen, cc per liter, "Atlantis" stations 1152 (34° 48'N, 55° 30'W, February 28, 1932), 1044 (36° 06'N, 57° 14'W, August 18, 1931), 1157 (35° 10'N, 44° 40'W, March 3–4, 1932), 1036 (37° 09'N, 43° 19'W, August 11, 1931), and vertical distribution of temperature at stations 1157 and 1036.

meters depth; its lower boundary between 860 and 1010 meters. Its thickness varied between 0[2] and 325 meters (fig. 3). Within it the oxygen content varied from 4.06 to 3.35 cc per liter, 60 to 55 per cent saturated, the average oxygen content[3] of the whole layer ranged from 3.89 to 3.61 cc per liter, 59.1 to 56.8 per cent of total saturation. The average temperatures and salinities of this layer were, respectively, 9.41° to 11.89° and 35.16 o/oo to 35.41 o/oo.

[2] At two stations in section A the minimum oxygen content failed to fall below 60 per cent of total saturation. This condition in the area of investigation is unusual.

[3] In this paper the average oxygen contents as well as the averages of other elements have been calculated directly from the observational data of each station.

Let $a_1, a_2, a_3, \cdots, a_n$ = the oxygen concentrations (or the concentrations of any other element) at the corrected depths of observation $x_1, x_2, x_3, \cdots, x_n$ and D = the total thickness of the layer under consideration. Then the average concentration for the water column within the layer

$$= \frac{\left[\frac{a_1 + a_2}{2}(x_2 - x_1)\right] + \left[\frac{a_2 + a_3}{2}(x_3 - x_2)\right] + \left[\frac{a_3 + a_N}{2}(x_N - x_3)\right]}{D}.$$

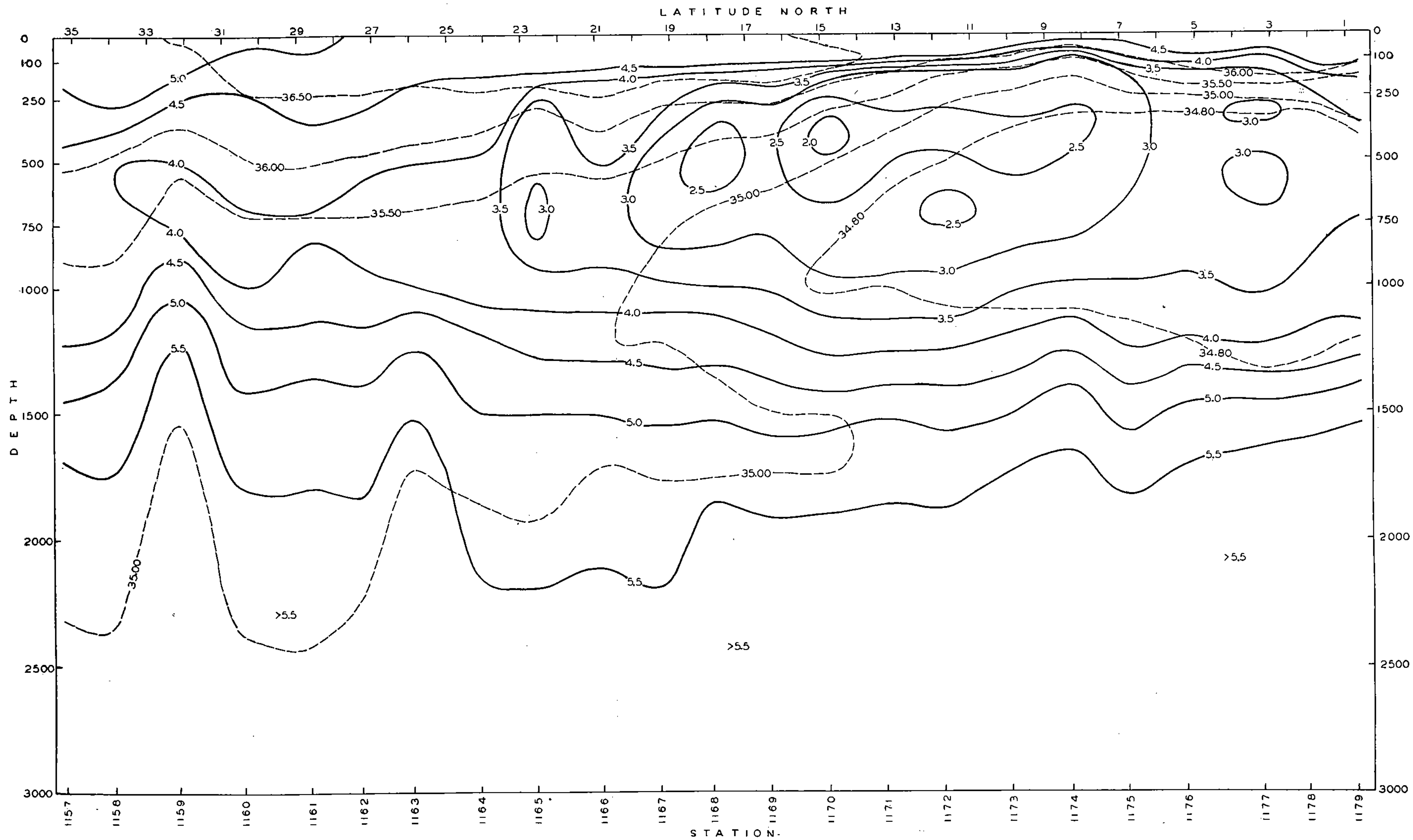

FIG. 5.—Distribution of oxygen, cc per liter, "Atlantis" section B (stations 1157–1179, latitude 35° 10′N to 0° 45′N, between longitudes 39° 47′W and 44° 40′W) March 1932.

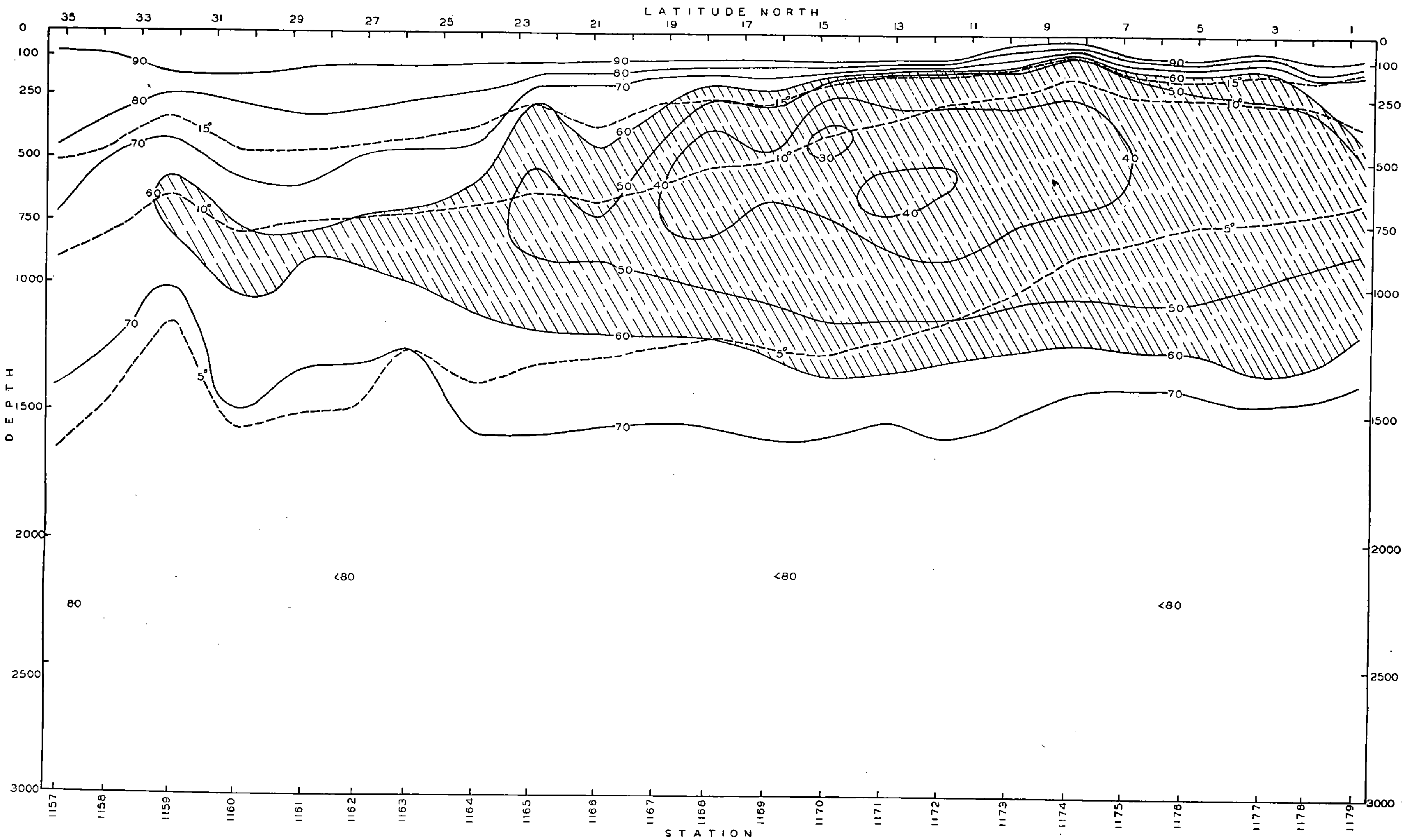

FIG. 6.—Distribution of oxygen, per cent of total saturation, "Atlantis" section B (stations 1157–1179, latitude 35° 10′N to 0° 45′N, between longitudes 39° 47′W and 44° 40′W) March 1932.

The oxygen content of the rich underlying oxygen layer reached a second maximum of about 6 cc per liter, 81 to 83 per cent of total saturation in the vicinity of 2000 meters depth, below which, with increasing depth, the oxygen content was relatively constant. This oxygen layer included by far the greater part of the water column. Its average oxygen content to 2000 meters depth varied between 72.73 and 77.75 per cent, 5.28 to 5.63 cc per liter; the average temperatures and salinities within these same boundaries were 4.38° to 4.85° and 34.99 o/oo to 35.04 o/oo.

Along 40th Meridian between Latitude 35°N and the Equator ("Atlantis" Section B)

For convenience of discussion and in order to emphasize regional differences in vertical oxygen distribution section B is divided into two parts.

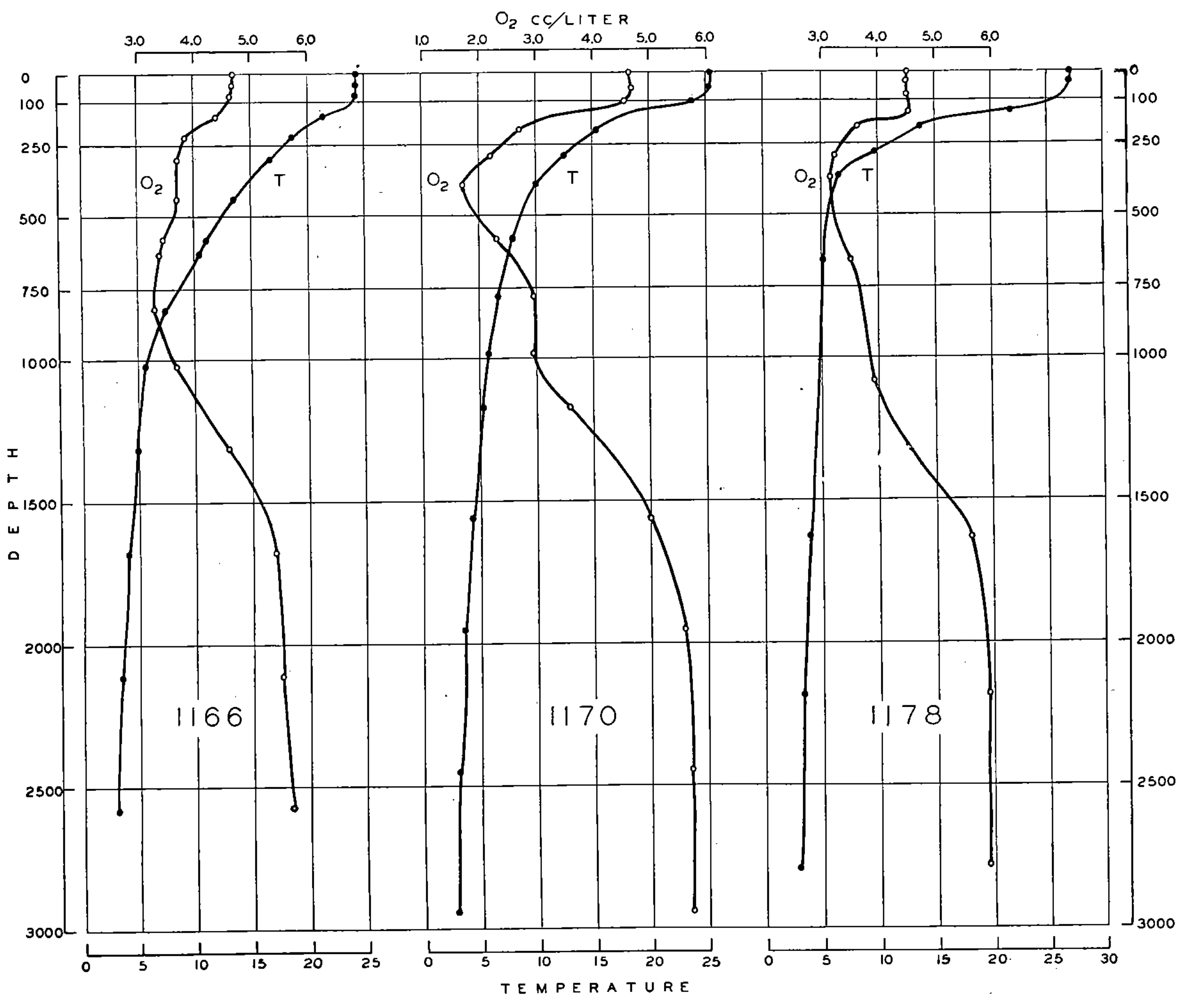

FIG. 7.—Vertical distribution of oxygen (cc per liter) and temperature at "Atlantis" stations 1166 (20° 50'N, 41° 38'W, March 10, 1932); 1170 (14° 47'N, 40° 58'W, March 13, 1932); 1178 (2° 2'N, 41° 18'W, March 20, 1932).

Latitude 35°–20°N. The maximum oxygen content occurs in the surface layer (95 to 98 per cent saturation, 4.70 to 5.32 cc per liter); absolute values, but not the per cent of saturation, decreasing from north to south with increased temperature of the surface water. From the surface downward the oxygen decreased to a minimum in the intermediate depths (between 940 and 600 meters) of 4.30 to 2.99 cc per liter, >60[4] to 45 per cent of total saturation. With increasing depth the oxygen again increased to a value between 5.34 and 6.03 cc per liter at 2000 meters depth below which it was relatively constant (table 2; figs. 5, 6, and 7).

Latitude 20°N–0°N. The maximum oxygen content as in the northern half of the section occurred in the surface layer (95 to 102 per cent saturated, 4.49 to 4.93 cc per liter), the absolute values being lower near the equator. The minimum concentrations are in general lower (1.73 to 3.45 cc per liter, 27 to 48 per cent of total saturation) and lie at shallower depths (340 to 640 meters) than in the northern half of the section. At 2000 meters the oxygen has increased to 5.42–5.85 cc per liter below which it is relatively constant (table 2; figs. 5, 6, 7).

TABLE 2

Station	North Latitude	West Longitude	Surface Oxygen cc/l	Surface Oxygen per cent	Minimum Oxygen depth	Minimum Oxygen cc/l	2000 Meter Oxygen
1157	35°10′	44°40′	5.29	96	830	4.30	5.82
1158	33°52′	44°03′	5.32	97	600	3.95	5.62
1159	32°09′	43°30′	5.25	96	640	3.70	6.03
1160	30°26′	42°53′	5.00	96	840	3.82	5.54
1161	28°38′	41°57′	5.10	98	800	3.87	5.62
1162	27°15′	41°45′	4.87	96	800	3.77	5.70
1163	25°53′	41°25′	4.96	98	940	3.53	5.57
1164	24°06′	41°26′	4.77	95	880	3.58	5.34
1165	22°35′	41°19′	4.77	97	780	2.99	5.39
1166	20°50′	41°38′	4.70	97	780	3.28	5.44
1167	19°17′	41°40′	4.76	98	640	2.62	5.42
1168	17°55′	41°30′	4.93	102	480	2.30	5.70
1169	16°22′	41°10′	4.68	97	480	2.52	5.58
1170	14°47′	40°58′	4.65	97	390	1.73	5.55
1171	13°15′	41°06′	4.71	98	400	2.40	5.70
1172	11°43′	40°54′	4.69	98	400	2.40	5.55
1173	9°57′	40°55′	4.72	98	473	2.30	5.72
1174	8°20′	40°45′	4.76	99	341	2.25	5.77
1175	6°50′	40°25′	4.49	96	440	2.70	5.74
1176	5°16′	39°47′	4.54	96	518	3.10	5.80
1177	3°13′	40°00′	4.65	99	548	2.89	5.85
1178	2°02′	41°18′	4.49	95	366	3.17	5.80
1179	0°45′	42°38′	4.61	99	600	3.45	5.80

Stations in section B. Minimum values range 60 to 27 per cent saturation and 2000 meter values range 80 to 73 per cent saturated. Minimum and 2000 meter values scaled from station curves.

Considering the section as a whole the precise courses followed by the isolines of 60 per cent saturation along this section are especially interesting because of the undulations they show from north to south. Thus, the upper 60 per cent isoline lies at approximately 800 meters depth at latitude 30°N, rises sharply southward to 200 meters at latitude 18°N and then gradually to 75 meters at latitude 8°N, after which it drops again to about 400 meters near the equator.

Above the upper 60 per cent isoline the oxygen content ranges from 5.3 cc per liter (surface maximum) to 3.2 cc per liter. The average oxygen content between 75 meters

[4] In section B, south of latitude 33°N, the minimum oxygen content was always less than 60 per cent. The occurrence of a minimum oxygen content greater than 60 per cent in the region investigated is very rare.

depth and the upper 60 per cent isoline varied from 4.42 to 3.4 cc per liter, 70.15 to 80.84 per cent of total saturation. At the isoline of 60 per cent the absolute oxygen values ranged from 3.9 cc per liter in the north to 3.2 cc per liter near 13°N latitude, corresponding to the elevation of this line toward the surface bringing it into warmer water so that 60 per cent of total saturation with dissolved oxygen is reached for lower absolute values. This condition is illustrated by table 3.

TABLE 3

Station	1159	1161	1167	1171	1174	1178
Lat. N.	32°09′	28°38′	19°15′	13°15′	8°20′	2°02′
Depth	570	800	300	145	75	240
T°	11.7°	9.4°	14.6°	18.8°	16.8°	13.6°
S o/oo	35.49	35.38	35.98	36.04	35.69	35.59
O_2 cc/l	3.7	3.9	3.5	3.2	3.4	3.6

The oxygen poor layer, as defined by values less than 60 per cent saturated, was absent entirely in the extreme northern part of the section (figs. 6, 34, 35, and 36; see page 41) but appears at latitude 32°–33°N and increases then southward in thickness to almost 1200 meters at latitude 15°N to continue 1100–1200 meters thick to latitude 2°N. The location of the upper boundary is stated above; the lower boundary lies between 800 meters in the northeastern Sargasso Sea and 1360 meters in the trade wind belt (fig. 6). The minimum oxygen content of the oxygen poor layer decreased both from the north and south to a minimum value of 1.7 cc per liter, 26.8 per cent of total saturation near latitude 15°N where the oxygen poor layer was thickest (table 4).

TABLE 4

Station	Latitude	Thickness	Minimum Value depth	cc/l
1161	28°38′	115	800	3.87
1164	24°06′	515	880	3.58
1166	20°50′	740	780	3.28
1168	17°55′	1000	480	2.30
1170	14°47′	1190	390	1.73
1174	8°20′	1155	340	2.25
1178	2°02′	1080	366	3.17

Relationship between value of minimum oxygen content and thickness of the oxygen poor layer of section B.

The average oxygen content[3] for the whole thickness of the oxygen poor layer decreased from 4 cc per liter, 60 per cent saturated, at the northern end to a minimum of 2.8 cc per liter, 42 per cent saturated near latitude 15°N, and then increased to 3.7 cc per liter, 53 per cent saturated near the equator. The average values when plotted against latitude show a series of undulations the significance of which is discussed on page 74.

The average oxygen content of the water between the lower isoline of 60 per cent and 2000 meters depth (rich underlying oxygen layer) decreased from 5.5 cc per liter (76.51 per cent saturated) in the north to a minimum of about 4.9 cc per liter between latitudes 23° and 16°N, and then increased to 5.4 cc per liter (75.22 per cent saturated) near the equator. The average values, when plotted against latitude, show a series of waves similar to those of the oxygen poor layer. In the water between 2000 and 3000 meters the average oxygen content decreased from 78.9 per cent of total saturation in the north to 73.1 per cent between latitudes 22° and 23°N and then increased to 78.8 per cent of total saturation near the equator.

[3] Ibid. Page 11.

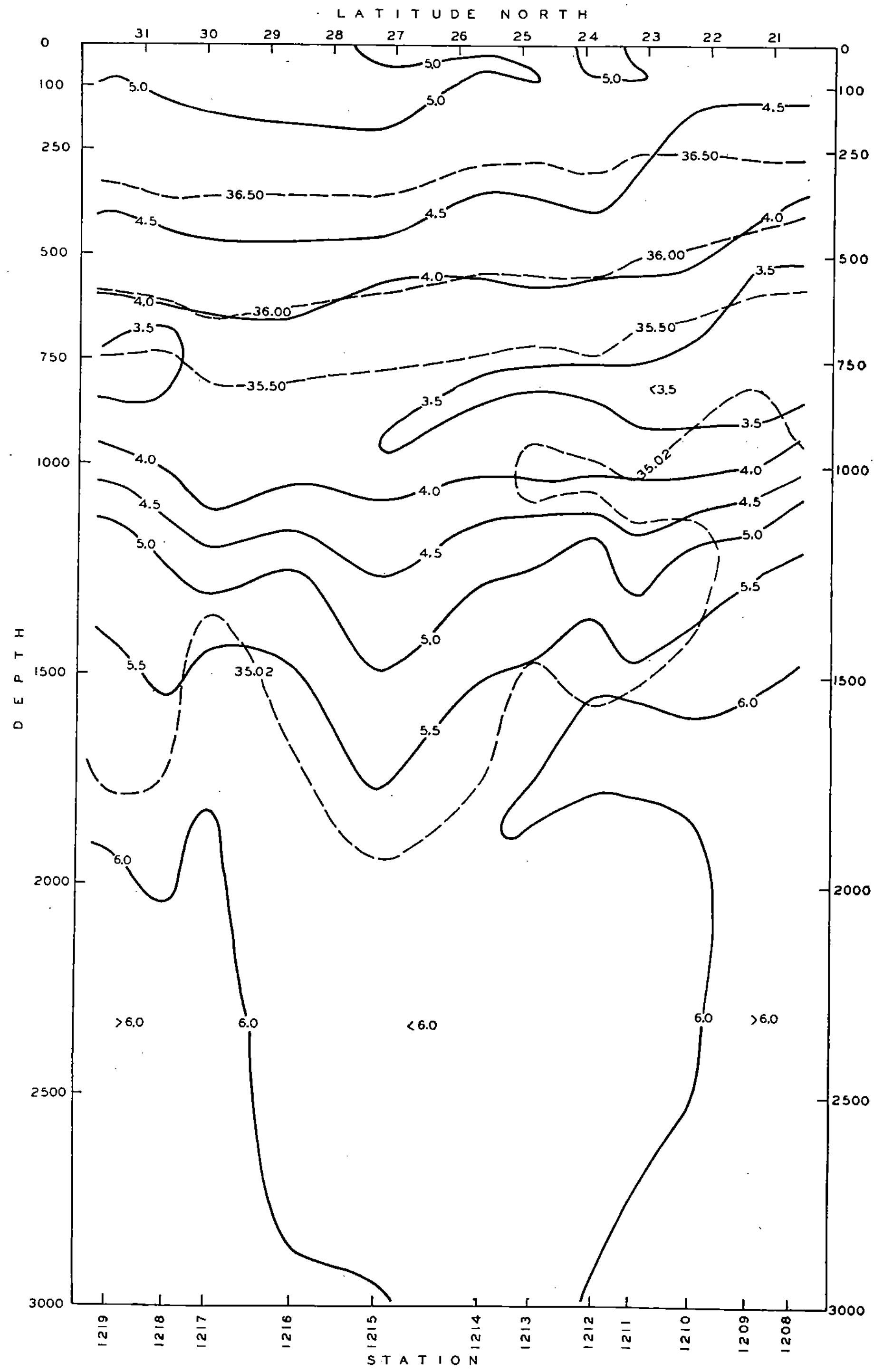

FIG. 8.—Distribution of oxygen, cc per liter, "Atlantis" section C (stations 1208–1219, latitude 20° 38′N to 31° 30′N, between longitudes 64° 31′W and 68° 36′W). April 1932.

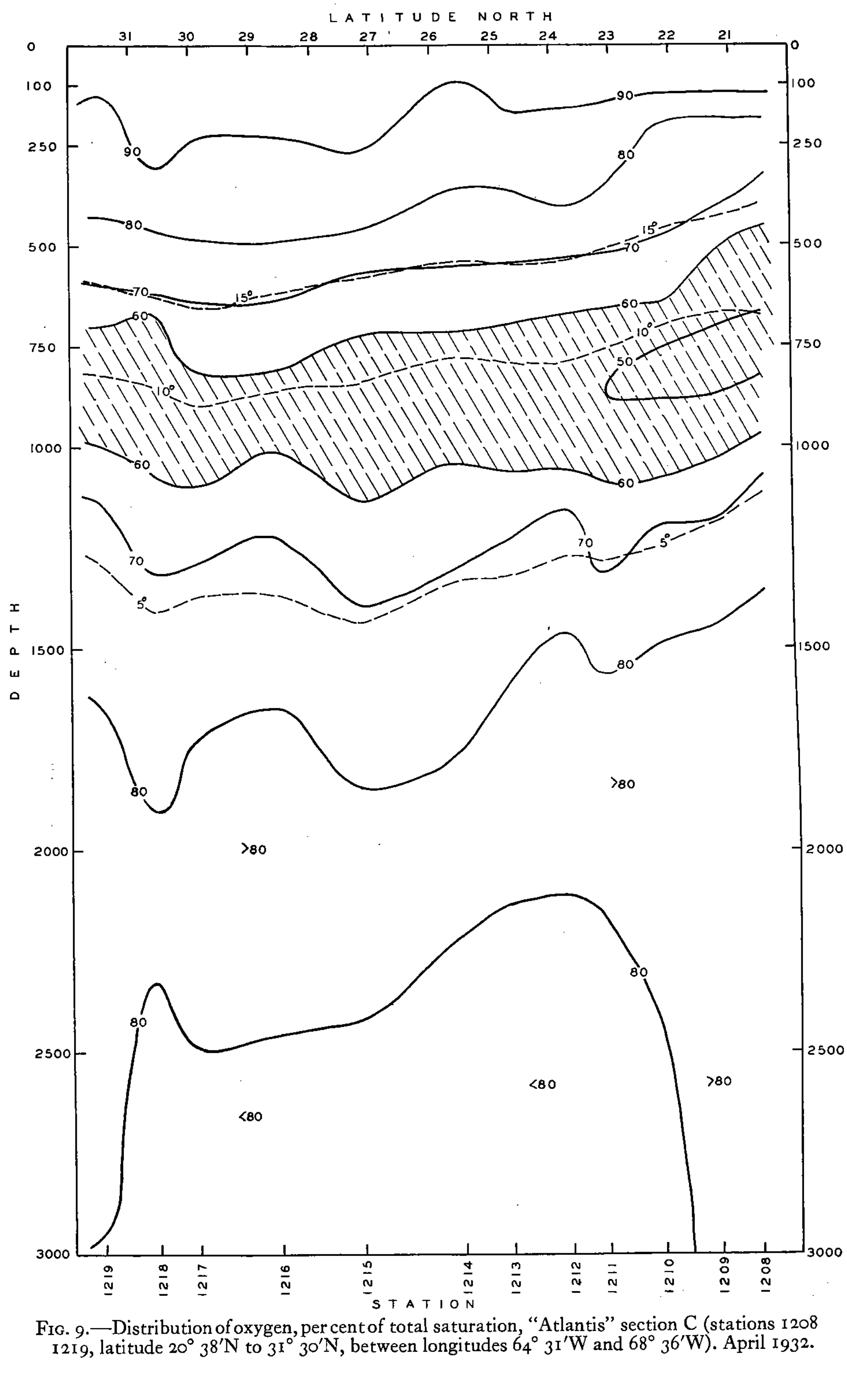

FIG. 9.—Distribution of oxygen, per cent of total saturation, "Atlantis" section C (stations 1208 1219, latitude 20° 38′N to 31° 30′N, between longitudes 64° 31′W and 68° 36′W). April 1932.

Thus, summarizing, the chief regional differences in the vertical oxygen distribution in section B are: (1) in thickness of the highly oxygen saturated surface layer; (2) in the value of the minimum oxygen concentration; (3) in the depth at which the minimum oxygen concentration occurs; (4) in the thickness of the midstratum characterized by low oxygen values.

Between Haiti and Bermuda ("Atlantis" Section C)

The oxygen content of the surface layer (4.7 to 5.2 cc per liter, 95 to 101 per cent saturated) decreased to a minimum of 3.15 to 3.7 cc per liter in the mid depths (table 5; figs. 8, 9, 10).

TABLE 5

Station	North Latitude	West Longitude	Surface Oxygen cc/liter	per cent	Minimum Oxygen depth	cc/liter	2000 Meter Oxygen
1208	20°38′	68°36′	4.68	97	795	3.20	6.1
1209	21°19′	68°13′	4.70	97	750	3.15	6.05
1210	22°14′	67°50′	4.86	99	800	3.18	5.95
1211	23°10′	67°34′	4.73	96	850	3.38	—
1212	23°46′	67°24′	5.06	101	800	3.36	5.93
1213	24°45′	67°05′	4.83	97	860	3.52	5.90
1214	25°33′	66°45′	4.93	97	800	3.53	5.97
1215	27°12′	66°11′	4.91	97	880	3.48	5.83
1216	28°33′	65°43′	5.22	99	820	3.65	5.94
1217	29°55′	65°15′	5.12	97	817	3.70	6.05
1218	30°35′	65°00′	5.18	98	740	3.45	6.00
1219	31°30′	64°31′	5.08	95	800	3.36	6.02

Stations in section C. Minimum values range from <60 to 48 per cent of total saturation and 2000 meter values from 80 to 82 per cent.

The upper boundary (60 per cent saturation isoline) of the oxygen poor midstratum lies deepest (810 meters) near Bermuda rising gradually to 460 meters near Haiti, corresponding to a rise of isotherms and isohalines (figs. 8, 9). The oxygen content of the water above this boundary ranged from the maximum surface value of 5.2 cc to 3.56 cc per liter (101 to 60 per cent saturated), the absolute values at 60 per cent isoline varied according to temperature and salinity from 3.8 to 3.56 cc per liter.

The oxygen poor layer of the midstratum (saturation values <60 per cent) varied in thickness from 205 to 520 meters, the maximum thickness as well as the closest surfaceward approach of its upper boundary occur in the southern part of the region (fig. 9). The lower boundary (lower 60 per cent saturation isoline) lies between 940 and 1150 meters depth. The average oxygen content for the thickness of the oxygen poor stratum decreased from 3.88 cc per liter (almost 60 per cent saturated) near Bermuda to 3.44 cc per liter (53 per cent saturated) in the southern part of the region (fig. 11). The average salinity of the oxygen poor layer ranged from 35.35 o/oo to 35.11 o/oo.

In the underlying water below the lower 60 per cent isoline the oxygen content increased to 5.8–6.1 cc per liter, >80 per cent saturated, at 2000 meters and then remained relatively constant. Between the lower 60 per cent isoline and 2000 meters depth the average oxygen content decreased from 5.47 cc per liter (76 per cent saturated) near Bermuda to a minimum value of 5.27 cc per liter (74 per cent saturated) at latitude 27°N and then increased to 5.77 cc per liter (79 per cent saturated) near Haiti.

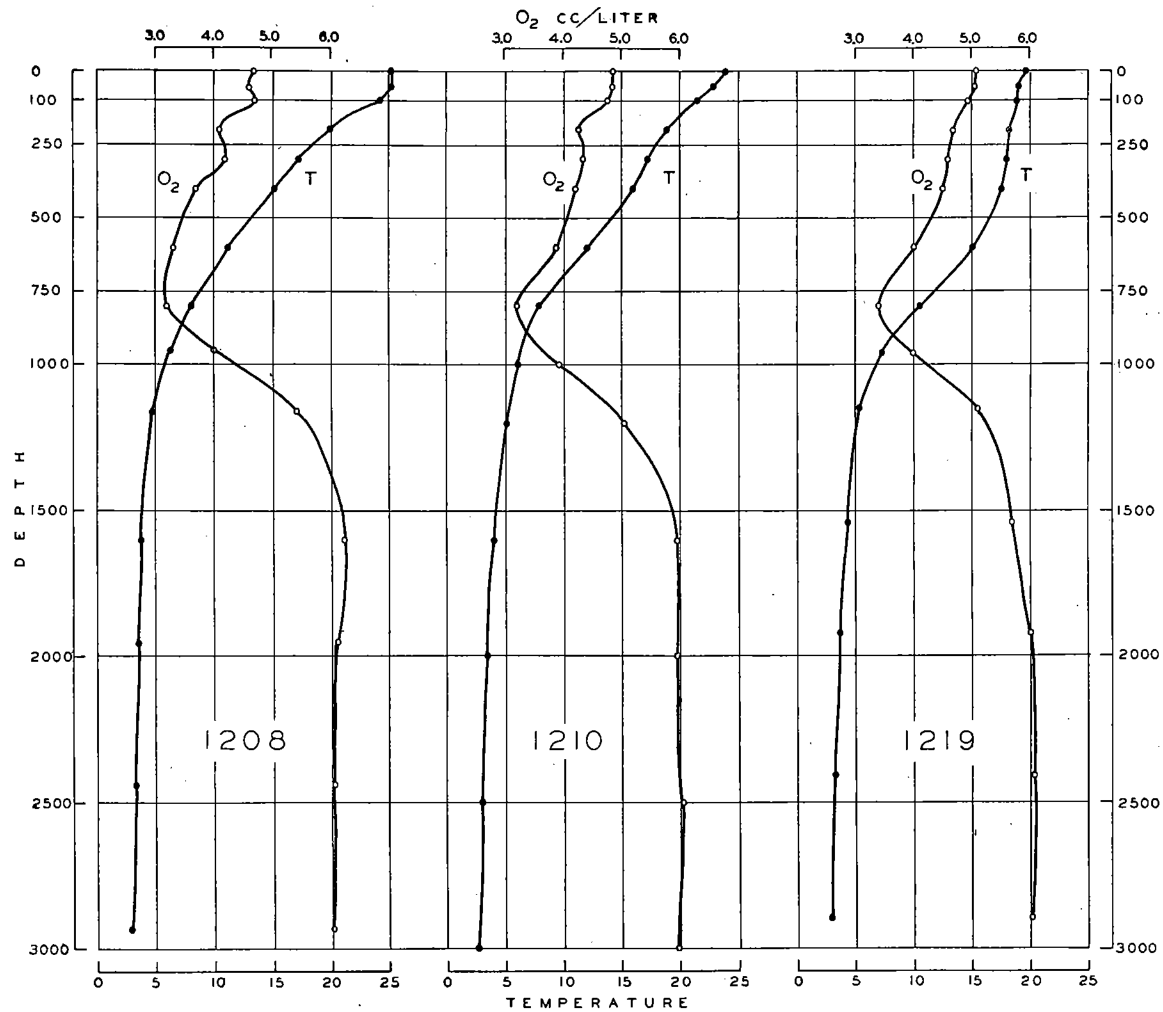

FIG. 10.—Vertical distribution of oxygen (cc per liter) and temperature at "Atlantis" stations 1208 (20° 38′N, 68° 36′W, April 7, 1932); 1210 (22° 14′N, 67° 50′W, April 8, 1932); 1219 (31° 30′N, 64° 31′W, April 13, 1932).

BETWEEN BERMUDA AND BAHAMA BANK ("ATLANTIS" SECTION D)

The change in vertical oxygen content along this section is illustrated by table 6. The upper boundary of the oxygen poor layer laid between 700 and 900 meters and the lower boundary between 940 and 1080 meters; the thickness was 160 to 340 meters. Within this layer the oxygen varied from 4.2 to 3.34 cc per liter, 60 to 51 per cent saturated (figs. 12, 13).

TABLE 6

Station	North Latitude	West Longitude	Surface Oxygen cc/liter	Surface Oxygen per cent	Minimum Oxygen depth	Minimum Oxygen cc/liter	2000 Meter Oxygen
1464	31°53′	65°25′	5.25	99	880	3.75	6.27
1465	31°25′	66°30′	5.58	106	950	3.74	6.40
1467	30°30′	68°30′	—	—	880	3.68	6.45
1469	29°26′	70°42′	5.17	100	800	3.50	6.18
1472	27°56′	73°53′	4.97	98	808	3.49	6.15
1473	27°35′	74°43′	4.89	97	900	3.34	6.50
1475	26°50′	76°09′	4.95	100	865	3.40	6.35
1476	26°42′	76°32′	4.89	100	780	3.48	6.21
1477	26°37′	76°45′	4.92	100	780	3.50	6.28

Stations in section D. Minimum values range from 51 to 58 per cent saturated and 2000 meter values from 84 to 88 per cent. Minimum and 2000 meter values scaled from curves.

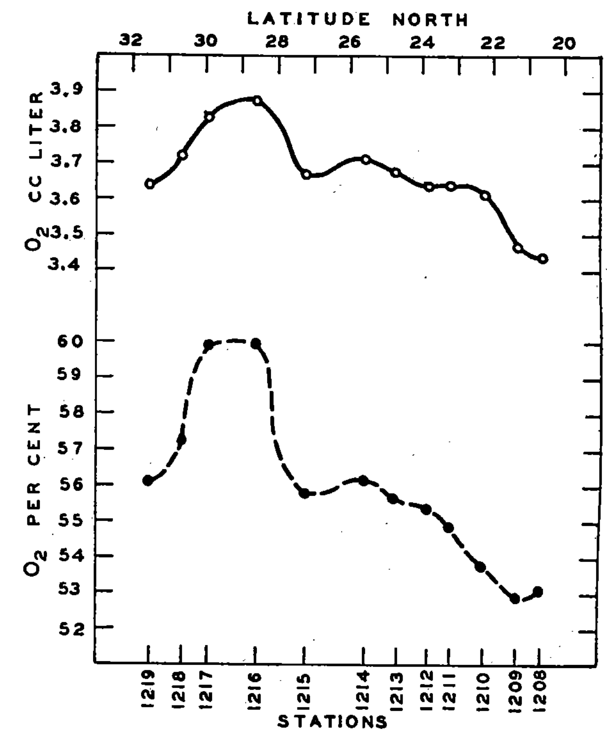

FIG. 11.—Average oxygen content of oxygen poor layer in "Atlantis" section C.

Region between Chesapeake Bay and Bermuda ("Atlantis" Section E)

The oxygen content decreased from the surface layers (4.87 cc–5.36 cc per liter, 94–100 per cent saturation) to a minimum (3.2–3.6 cc per liter, 59–49 per cent saturation) which, east of longitude 72° 30′W, occurs usually between 750 and 1050 meters and west of longitude 73°W is usually between depths of 200 and 400 meters (table 7). The increase in oxygen below the minimum continues to about 2000 meters depth (6.09–6.28 cc per liter) east of longitude 72° 30′W, but only to about 1000 meters or even less west of longitude 73°W (figs. 14, 15, 16). The division which marks the abrupt change in vertical distribution of oxygen in section E is a thermal convergence and is discussed in detail on page 56.

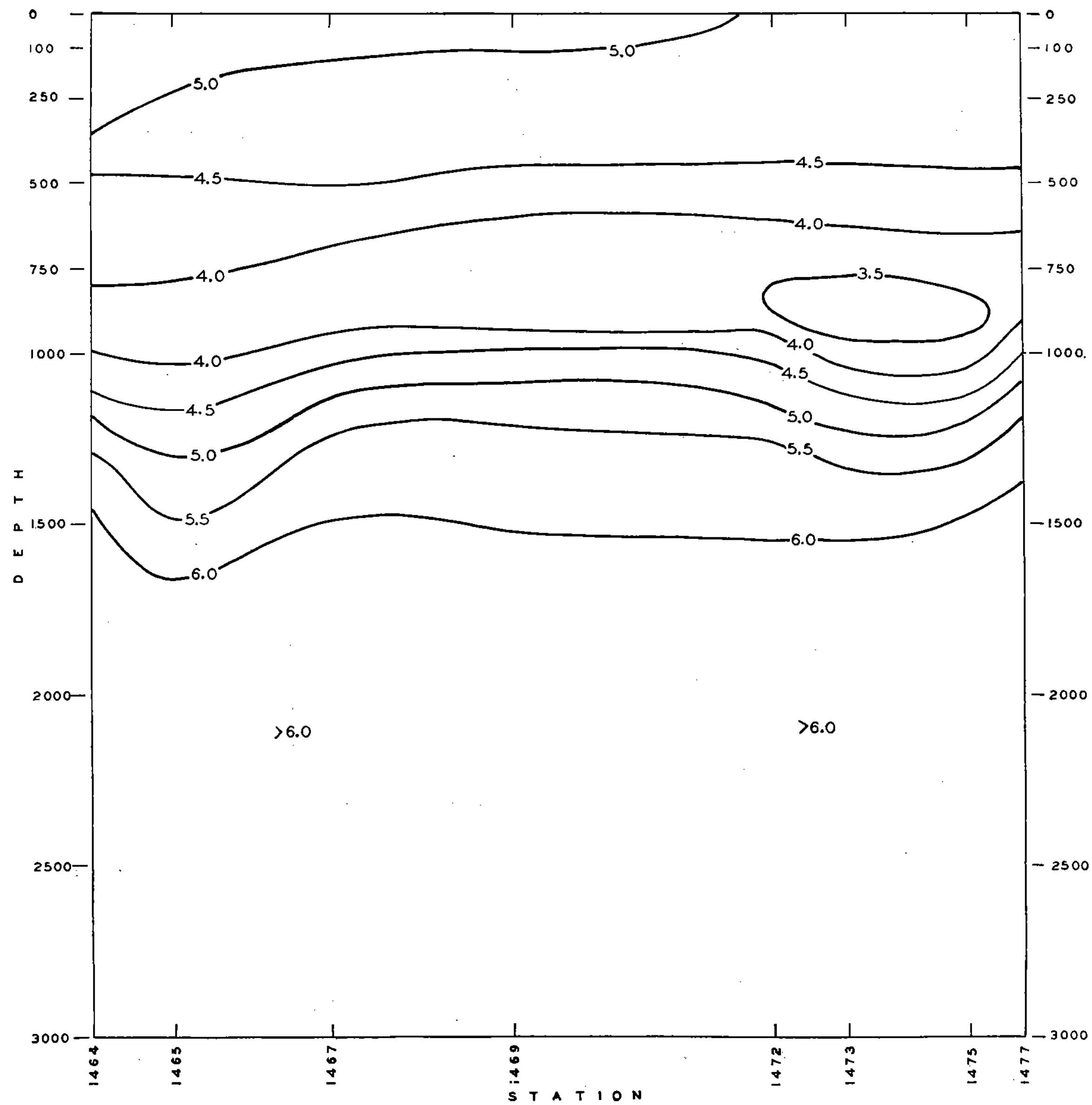

FIG. 12.—Distribution of oxygen, cc per liter, "Atlantis" section D (stations 1464–1477, latitude 31° 50′N to 26° 37′N between longitudes 65° 24′W and 76° 53′W). February 1933.

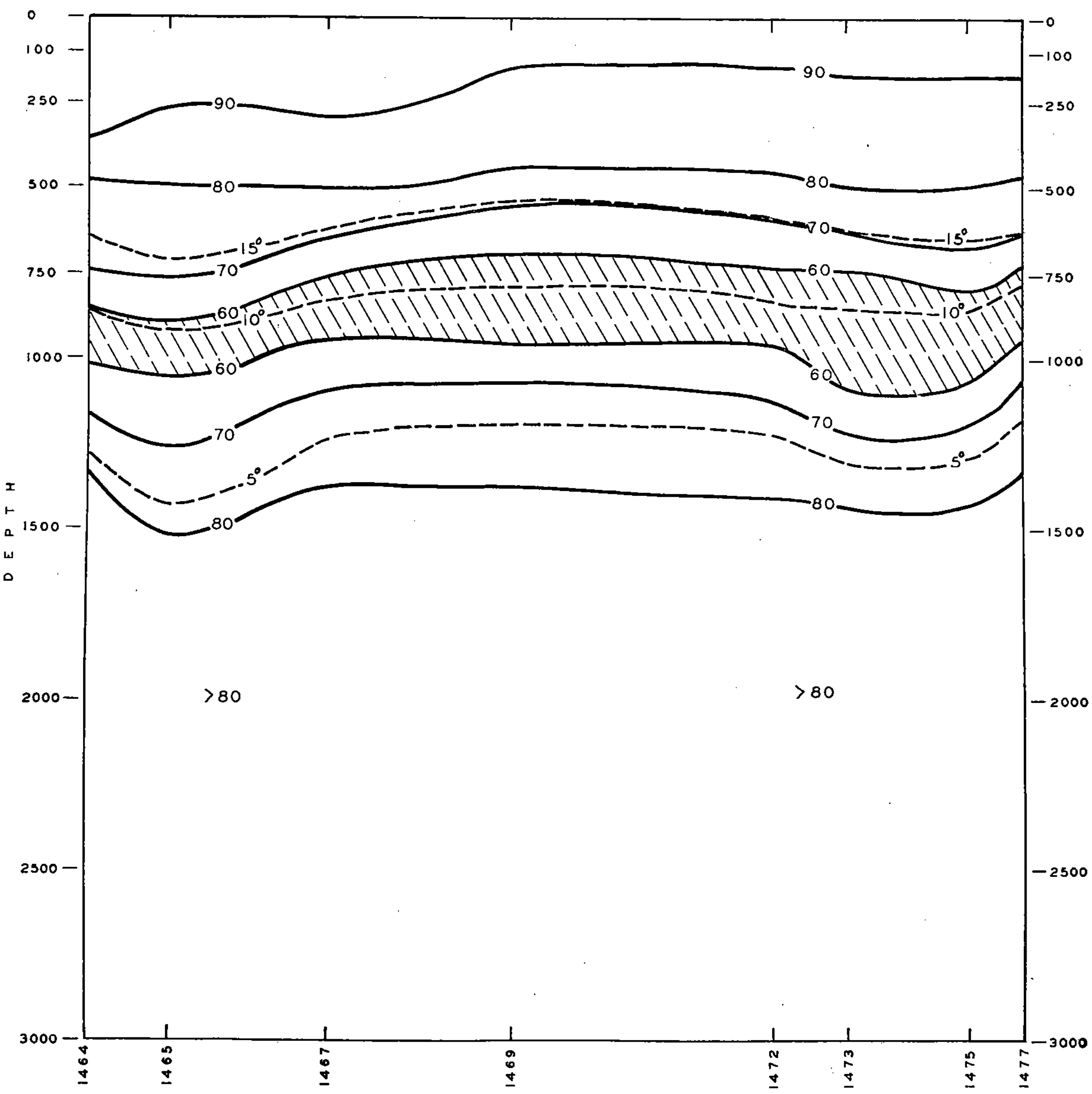

FIG. 13.—Distribution of oxygen, per cent of total saturation, "Atlantis" section D (stations 1464–1477, latitude 31° 50′N to 26° 37′N between longitudes 65° 24′W and 76° 53′W). February 1933.

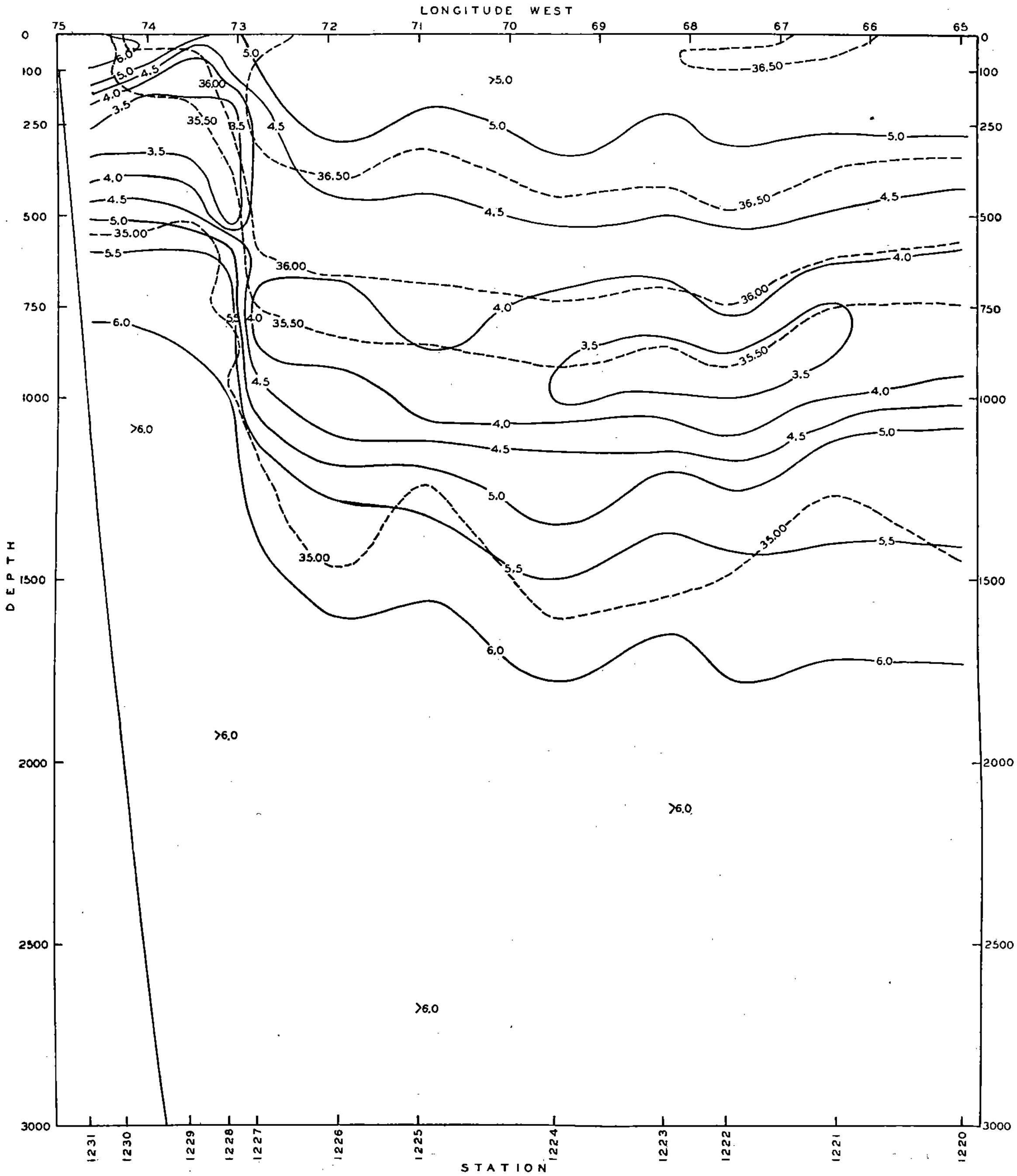

FIG. 14.—Distribution of oxygen, cc per liter, "Atlantis" section E (stations 1220–1231, between Bermuda and Chesapeake Bay). April 1932.

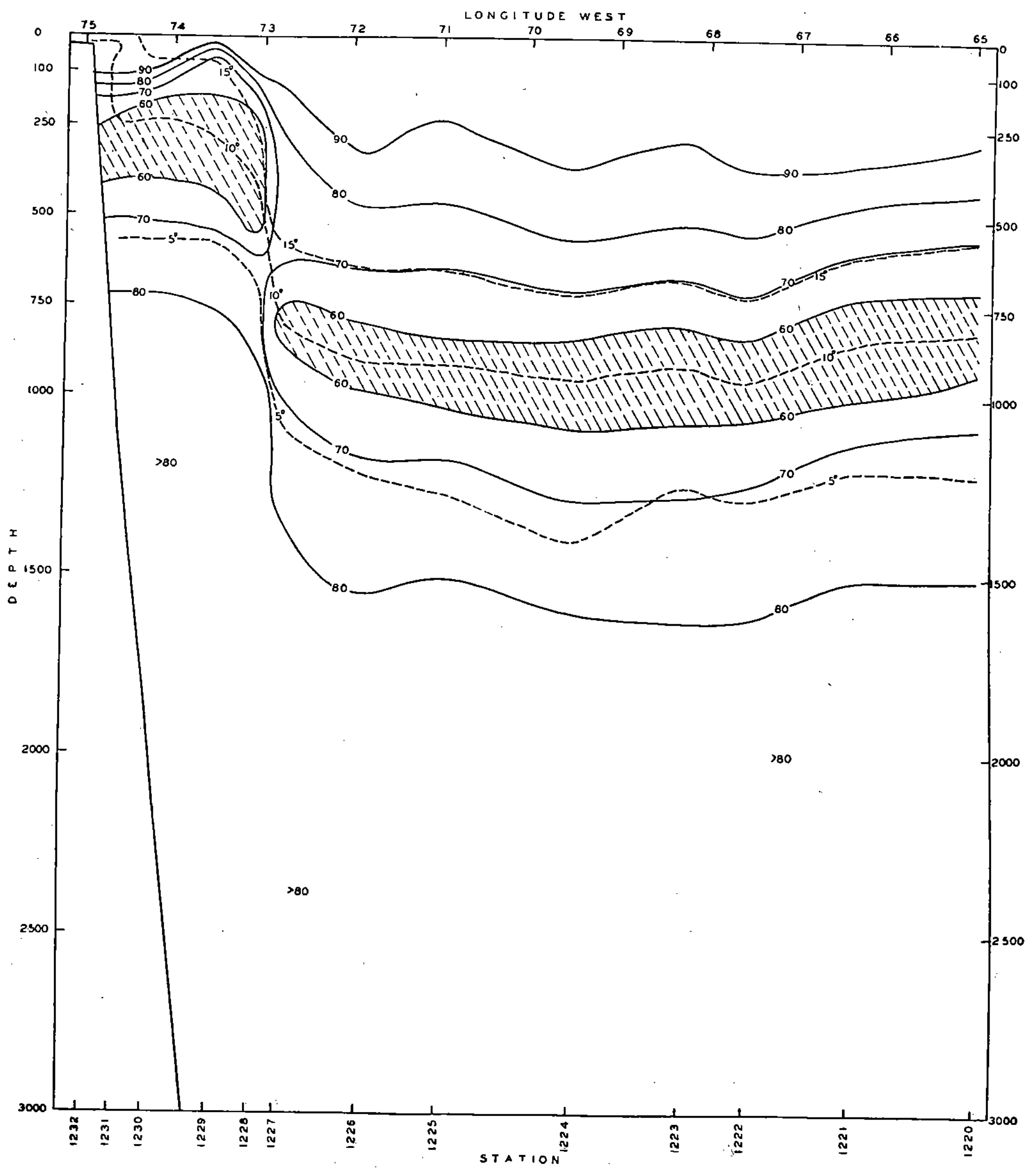

FIG. 15.—Distribution of oxygen, per cent of total saturation, "Atlantis" section E (stations 1220–1231, between Bermuda and Chesapeake Bay). April 1932.

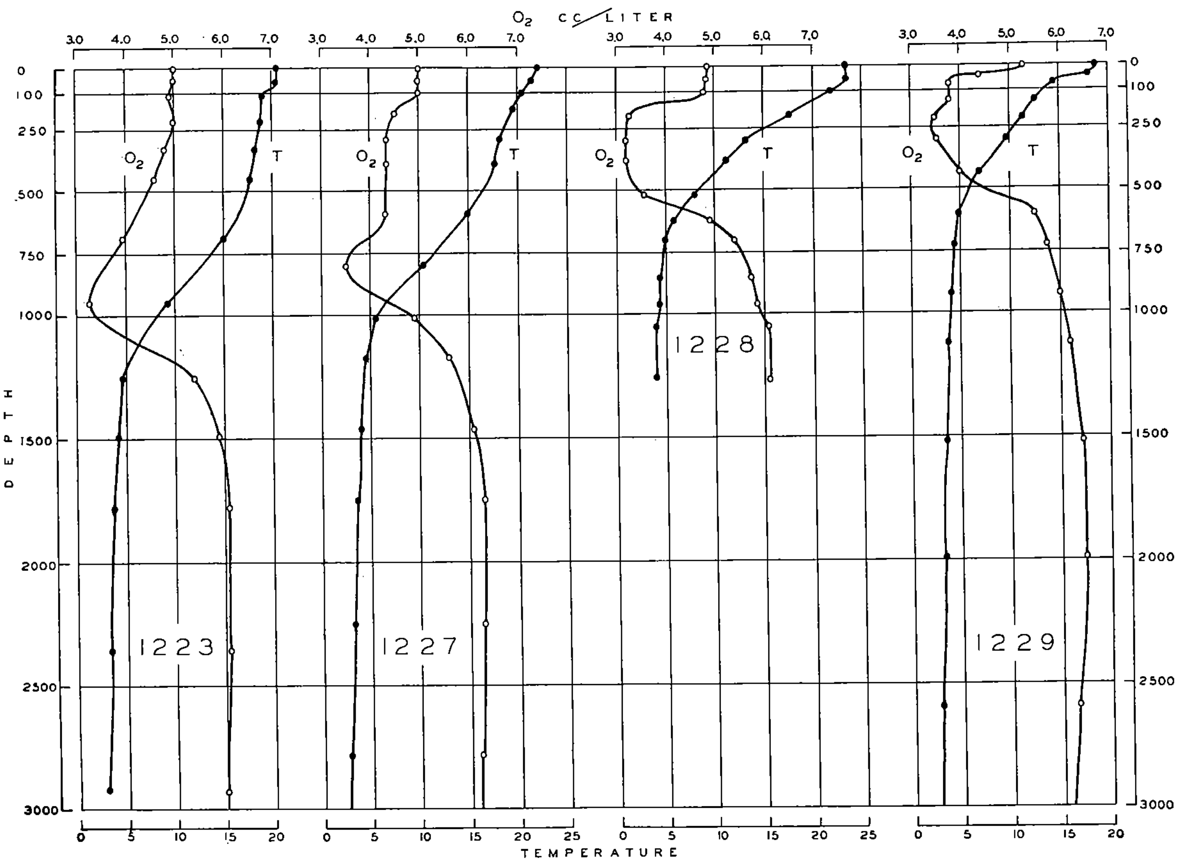

FIG. 16.—Vertical distribution of oxygen, cc per liter, and temperature at "Atlantis" stations 1223 (33° 41'N, 68° 18'W, April 19, 1932); 1227 (35° 38'N, 72° 47'W, April 21, 1932); 1228 (35° 57'N, 73° 05'W, April 21–22, 1932); 1229 (36° 12'N, 73° 32'W, April 22, 1932).

TABLE 7

Station	North Latitude	West Longitude	Surface Oxygen cc/liter	Surface Oxygen per cent	Minimum Oxygen depth	Minimum Oxygen cc/liter	2000 Meter Oxygen
1220	32°40'	65°00'	5.18	96	729	3.57	6.12
1221	32°51'	66°25'	5.02	94	769	3.32	6.09
1222	33°15'	67°35'	5.01	96	1035	3.63	—
1223	33°41'	68°18'	5.02	95	946	3.27	6.07
1224	34°10'	69°31'	5.29	99	993	3.52	6.09
1225	34°43'	71°00'	5.32	99	1000	3.59	6.25
1226	35°07'	71°53'	5.34	99	798	3.64	6.20
1227	35°38'	72°47'	4.97	97	797	3.52	6.28
1228	35°57'	73°05'	4.87	98	202–505	3.2–3.4	—
1229	36°12'	73°32'	5.28	98	213–284	3.5–3.5	6.50
1230	36°27'	74°15'	5.36	100	200–300	3.2–3.4	6.45

Stations in section E. Minimum values range from 49 to 59 per cent of total saturation; 2000 meter values from 83 to 87 per cent.

The vertical distribution of oxygen in this section differs from that of all others previously discussed in that between the approximate longitudes of 72° 30′W and 73°W (between stations 1227 and 1228), in the region of the thermal convergence, the oxygen poor stratum undergoes a change in level and as far as can be determined within this convergence minimum values do not fall below 60 per cent saturation so that the oxygen poor stratum as defined actually disappears (fig. 15). The theoretical importance of this is discussed on page 56.

East of station 1227 (72° 47′W) the upper boundary of the oxygen poor layer (upper 60 per cent isoline) lies between 700 and 850 meters, the lower boundary (lower 60 per cent isoline) between 860 and 1090 meters, and the thickness varies between 110 and 280 meters. West of station 1228 (73° 05′W) the upper boundary of the oxygen poor layer lies between 170 and 225 meters, the lower boundary between 400 and 550 meters and the thickness is 215 to 320 meters. The average oxygen content of the oxygen poor layer on both sides of the convergence is almost the same being 3.60 cc per liter, 57 per cent saturated east of station 1227 and 3.47 cc per liter, 54 per cent saturated west of station 1228. The average temperature and salinity is also similar being 9.92° and 35.34 o/oo east of station 1227 and 9.85° and 35.29 o/oo west of station 1228.

In the water underlying the lower boundary of the oxygen poor layer the average oxygen content increased from east to west. Thus, at station 1220 (65° 00′W), near Bermuda, the average oxygen content to 2000 meters depth was 5.52 cc per liter, 76.77 per cent saturated; while at station 1229 (73° 32′W), west of the convergence, it was 6.32 cc per liter, 84.01 per cent saturated. The east west oxygen distribution is discussed in detail on page 53.

Between Bermuda and Nova Scotia
("Atlantis" Section F)

The vertical distribution of oxygen is distorted by the three temperature convergences (page 59) which the section crosses (figs. 17, 18, 19). Thus, the surface values of 4.60 to 5.82 cc per liter, 97 to 109 per cent saturated, decrease to minimum values of 3.08 to 3.64 cc per liter, 58–49 per cent saturated, which lie at about 800 meters depth south of the convergences and between 200 and 770 meters within the three convergences in the northern half of the section (table 8). The oxygen gradient below the minimum concentration persists to about 2000 meters depth south of the convergences but in the convergences it may cease at shoaler depths (as in the thermal convergence off Chesapeake Bay; figs. 17, 18).

TABLE 8

Station	North Latitude	West Longitude	Surface Oxygen cc/liter	Surface Oxygen per cent	Minimum Oxygen depth	Minimum Oxygen cc/liter	2000 Meter Oxygen
1343	42°06′	64°50′	5.82	103	200	3.39	—
1344	41°42′	64°41′	4.96	97	257–346	3.25	6.4
1345	41°12′	64°28′	4.60	98	333–468	3.47–3.44	6.68
1347	40°15′	64°10′	4.70	99	590–772	3.53–3.64	6.14
1349	38°58′	64°30′	4.84	100	200	3.08	6.30
1351	37°37′	63°50′	4.63	101	800	3.28	6.32
1354	35°40′	63°00′	5.15	109	800	3.36	6.03
1356	33°47′	63°09′	4.63	99	800	3.53	6.09

Stations in section F. Minimum values range 49 to 58 per cent of total saturation; 2000 meter values from 81 to 89 per cent.

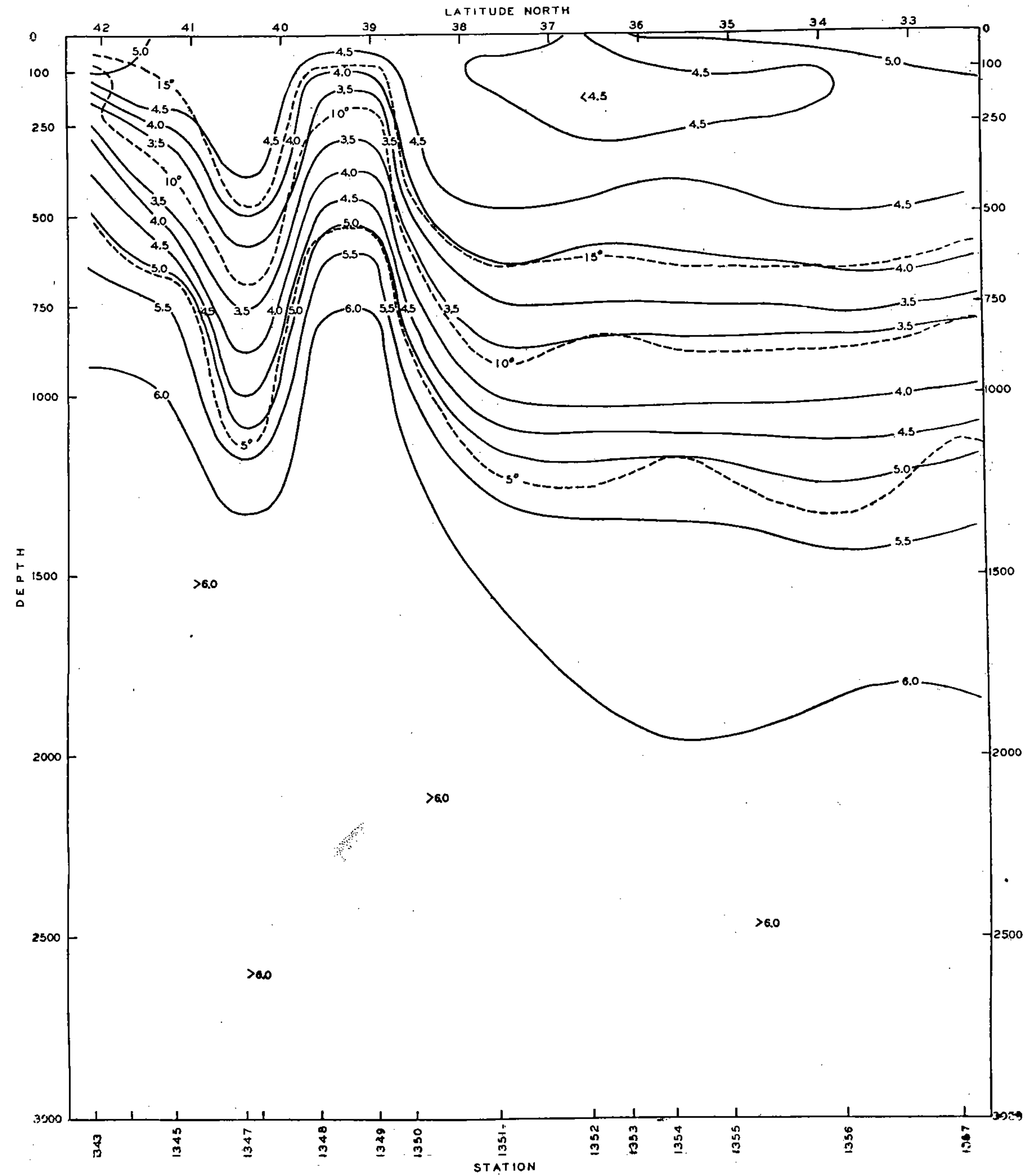

Fig. 17.—Distribution of oxygen, cc per liter, "Atlantis" section F (stations 1343–1357, between Bermuda and Nova Scotia). August 1932.

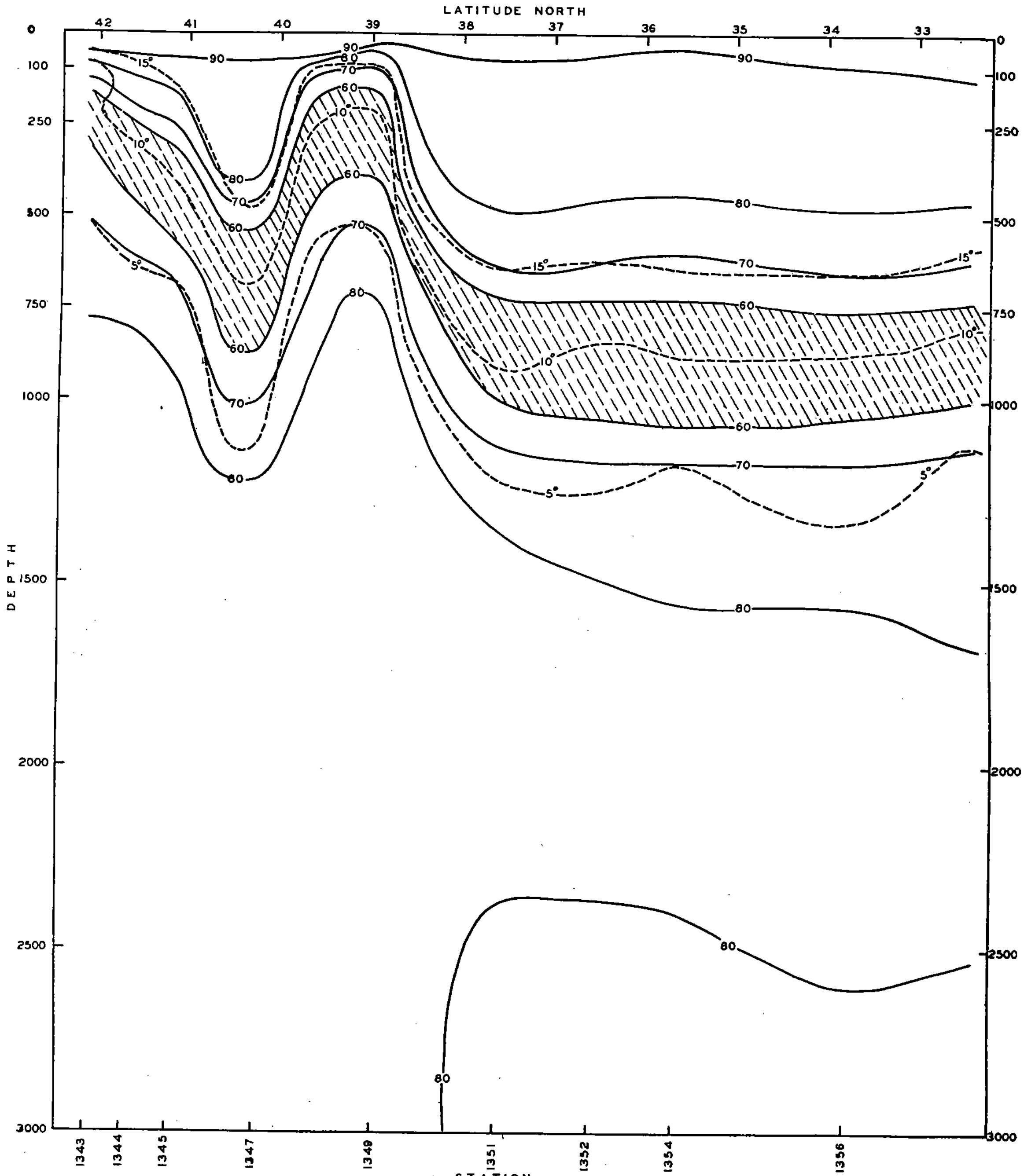

FIG. 18.—Distribution of oxygen, per cent of total saturation, "Atlantis" section F (stations 1343–1357, between Bermuda and Nova Scotia). August 1932.

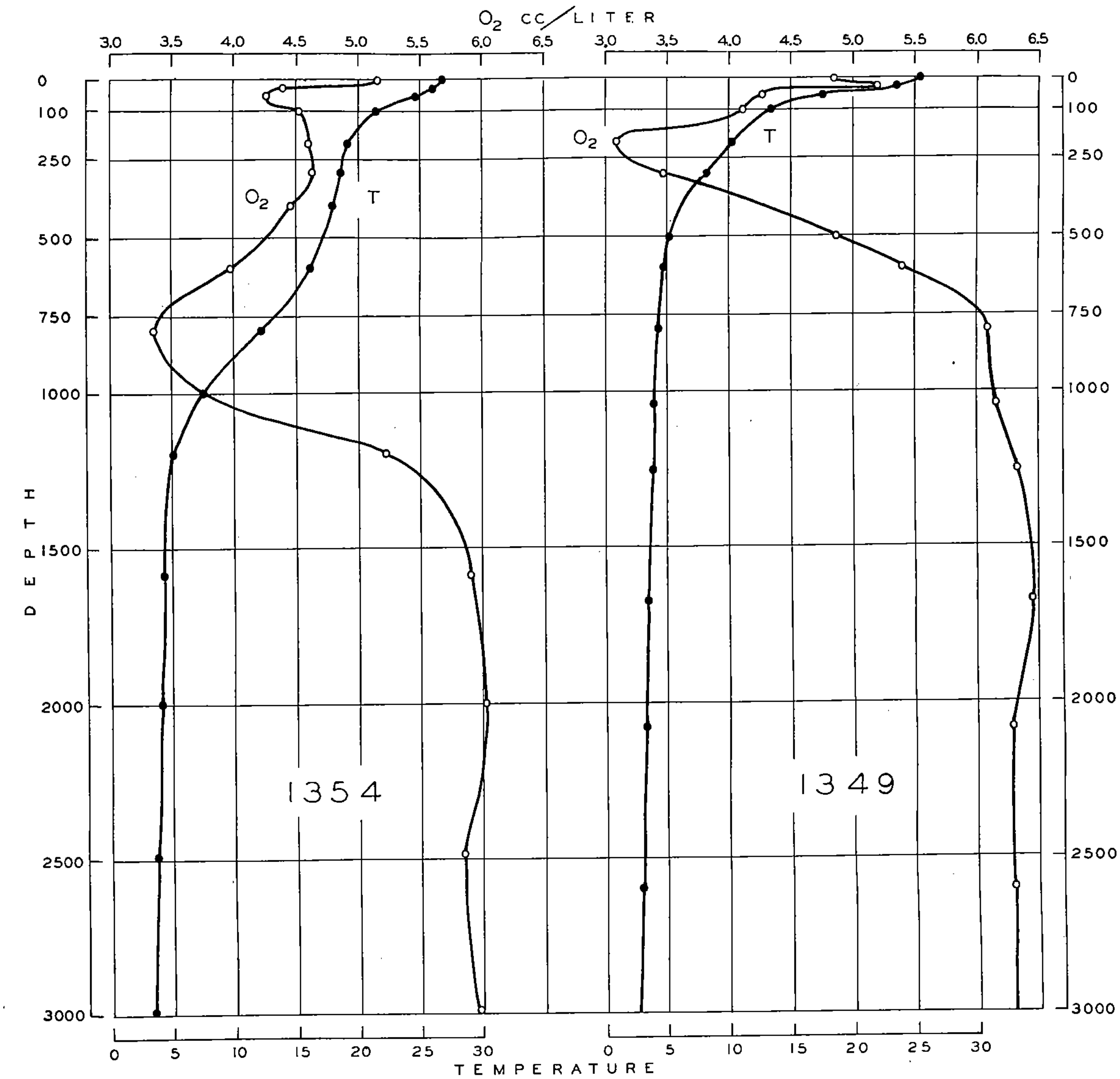

FIG. 19.—Vertical distribution of oxygen (cc per liter) and temperature at "Atlantis" stations 1354 (35° 40′N, 63° 00′W, August 19, 1932) and 1349 (38° 58′N, 64° 30′W, August 17, 1932).

The oxygen poor layer in section F (like that of section E) undergoes a change of level and thickness within the thermal convergences, but unlike that of section E (as far as our observations show) it does not disappear in any of the convergences (page 41), i.e., the minimum oxygen values within the convergence are all below 60 per cent of total saturation (fig. 18). The oxygen poor layer lies at a higher level after passing through the first or most southerly convergence than in the water to the south; it descends into deeper water within the second convergence whereas it is again raised in the third or most northerly convergence. Thus, the upper boundary of the oxygen poor layer (upper 60 per cent isoline) lies at a depth of 725 to 760 meters between Bermuda and latitude 37° 37'N (sta. 1351) to the north of which, after passing through the first convergence, it rises to a depth of 160 meters then descends to 540 meters in the second convergence and again rises to 170 meters in the third convergence at latitude 42°N (sta. 1343). Similarly, the lower boundary of the oxygen poor layer which, between Bermuda and the beginning of the first convergence, lies at depths of 970 to 1070 meters, rises to 380 meters, descends to 880 meters and then again rises to 315 meters. The thickness ranges from 275 to 340 meters south of the first convergence, and from 145 to 340 meters within the thermal convergences.

DISCUSSION OF THE VERTICAL DISTRIBUTION OF OXYGEN

Relationship to Vertical Distribution of Temperature

Temperature distribution may influence oxygen distribution in the following ways. First, a temperature gradient developed in the upper layers increases stability so that convection currents are reduced and consequently the underlying water must depend more and more on horizontal currents for the oxygen supply. Second, the presence of a well developed temperature and consequently a density gradient near the surface will cause the decay of sinking organic debris (of similar specific gravity) to occur at a higher horizontal level than in regions where such a gradient is absent or less well developed. A third effect on the vertical oxygen distribution may result from the vertical distribution of living organisms being influenced by the vertical temperature distribution.

North of latitude 30°N and extending to the vicinity of the thermal convergences off the American coast, (page 56) in the region of investigation the vertical distribution of temperature is characterized by the facts that the main thermocline lies between depths of 300–500 and 1200–1400 meters, and that the vertical decrease in oxygen content generally commences at about the same depth as the thermocline. South, west and northwest of this area the thermocline lies closer to the surface. The variation of temperature in the area is illustrated by the depth of 5°, 10°, and 15° isotherms in table 9.

In the northern part of the area (north of 30°N, but exclusive of the American coastwise convergence) the relationship of oxygen distribution to temperature is represented by section A (figs. 2, 3), the northern part of section B (figs. 5, 6), the eastern part of section E (figs. 14, 15), the southern half of section F (figs. 17, 18), and the vertical distribution curves of oxygen and temperature for stations 1036, 1157, 1044, 1152 (fig. 4), 1219

TABLE 9

North South Distribution of Temperature along 40th Meridian
("Atlantis" Section B)

Isotherm	Latitude 35°10'N (1157)	Latitude 20°50'N (1166)	Latitude 8°20'N (1174)	Latitude 0°45'N (1179)
15°	515	375	85	150
10°	900	675	175	360
5°	1650	1300	890	675

North South Distribution, South of Bermuda, near 65th Meridian
("Atlantis" Section C)

Isotherm	Latitude 31°30'N (1219)	Latitude 28°33'N (1216)	Latitude 23°46'N (1212)	Latitude 20°38'N (1208)
15°	600	615	540	400
10°	820	860	790	670
5°	1290	1370	1270	1130

North South Distribution, North of Bermuda, near 65th Meridian
("Atlantis" Section F)

Isotherm	Latitude 41°42'N (1344)	Latitude 40°15'N (1347)	Latitude 39°36'N (1348)	Latitude 37°37'N (1351)	Latitude 32°30'N (1357)
15°	70	470	90	645	600
10°	285	685	250	920	810
5°	620	1130	570	1225	1130

East West Distribution, East of Bermuda, near Latitude 34°N
("Atlantis" Section A)

Isotherm	Longitude 62°35'W (1147)	Longitude 57°07'W (1151)	Longitude 51°45'W (1154)	Longitude 44°40'W (1157)
15°	580	600	600	515
10°	820	840	820	900
5°	1130	1330	1270	1650

Southeast Northwest Distribution, between Bermuda and Chesapeake Bay
("Atlantis" Section E)

Isotherm	Longitude 65°00'W (1220)	Longitude 71°53'W (1226)	Longitude 73°05'W (1228)	Longitude 73°32'W (1229)	Longitude 74°15'W (1230)
15°	560	650	250	75	60
10°	815	905	420	285	235
5°	1215	1220	690	575	575

Depth of 5°, 10° and 15° isotherms in various "Atlantis" sections illustrating regional variation in vertical temperature distribution.

(fig. 10), 1223, 1227 (fig. 16), and 1354 (fig. 19). Thus, east of Bermuda the vertical relationship between oxygen and temperature distribution is illustrated by conditions at station 1157 (fig. 4), where the uniform temperature layer extended to a depth of about 350 meters (17.8° to 17.4°), the principle part of the thermocline extending to 1400 meters (6.2°). The oxygen content is 5.29 cc per liter (96 per cent saturated) at the surface, 4.75 cc per liter at 350 meters and decreases to a minimum of 4.00 cc per liter, 61 per cent saturation at 1000 meters depth. There is no well developed boundary surface present (on account of winter conditions), the oxygen gradient being everywhere gradual, and the region of minimum concentration lies well within the thermocline. From Bermuda westward to longitude 72° the relationship of oxygen and temperature is illustrated by station 1223 (fig. 16). Here the principle part of the thermocline begins at about 450 meters and extends below 1200 meters, the oxygen content is high and relatively uniform to a depth of more than 200 meters (4.90–5.02 cc per liter, 91 to 95 per cent saturated); the minimum of 3.27 cc per liter, 50 per cent saturated, occurs in the thermocline at 950 meters depth. North of Bermuda at station 1354 (fig. 19) at the time of observation the main thermocline laid between 400 meters and 1200 meters (18° to 5.2°). There was also a temporary thermocline in the upper 200 meters, the result of summer warming. But oxygen distribution shows but little effect from it, the highly saturated surface oxygen layer extending to a depth of more than 300 meters. Variations naturally occur above this depth due to photosynthesis and respiration but the oxygen does not begin appreciably to decrease until below 300 meters depth. Between 300 and 800 meters the oxygen decreases from 4.6 to a minimum of 3.3 cc per liter, the minimum lying in the thermocline.

In the thermal convergences paralleling the American coast the decrease in thickness and depth of the oxygen poor layer from east to west has been described previously (page 27). The correspondence of vertical oxygen and temperature distribution in the western part of the thermal convergence off Chesapeake Bay is illustrated by station 1228 (35° 57′N, 73° 05′W; fig. 16) where the thermocline lies between 100 and 700 meters (21.9°–4.9°). The highly oxygenated surface layer extends to about 125 meters (approximately 98 per cent saturated); the minimum oxygen content involves a stratum 300 meters thick (it being 3.18 to 3.37 cc per liter, 50–59 per cent saturated, between 200 and 500 meters depth) and the lower oxygen gradient ends at about 1050 meters depth (6.06 cc per liter, 83 per cent saturated).

West of the thermal convergence off Chesapeake Bay where all isolines have reached the highest horizontal level the conditions are illustrated by station 1129 (36° 12′N, 73° 32′W; fig. 16). Here the main thermocline lies between 50 and 600 meters (17.0°–4.8°), the highly saturated surface layer of oxygen is less than 35 meters thick, with oxygen decreasing from 5.28 cc per liter (98 per cent saturated) at the surface to a minimum of 3.5 cc per liter (54–57 per cent saturated) at 200 to 300 meters depth. At 1120 meters the oxygen content is 6.20 cc per liter (85 per cent saturated).

Further north, off Nova Scotia, where three thermal convergences, instead of only one, occur (page 59) the vertical distribution of oxygen and temperature correspond as they do in the single convergence off Chesapeake Bay (figs. 14, 15, 17, 18). Thus, at station 1349 (38° 58′N, 64° 30′W; fig. 19) which lies on the north side of the most southerly or principle convergence off Nova Scotia the thermocline begins very close to the surface[5]

[5] The fact that the thermocline lies so close to the surface is due to the warming of the surface layer in summer; the main thermocline begins at about 100 meters.

(less than 25 meters) and extends to a depth of about 600 meters, the temperature decreasing from 25.5° to 4.5°. The highly oxygen saturated surface layer is very thin, the oxygen decreasing from 5.20 cc per liter (104 per cent saturated) at 25 meters depth to a minimum of 3.08 cc per liter (48 per cent saturated) at 200 meters depth, below which it increases to 6.1 cc per liter, 84 per cent saturated, at 800 meters.

Thus, in the principle or first thermal convergence at points off both Chesapeake Bay and Nova Scotia the vertical distribution of oxygen in following the vertical temperature distribution results in the fact that the highly saturated surface layer is in either case not over 100 meters in thickness, the minimum concentrations, 3.1 to 3.3 cc per liter, are approximately the same and occur at about the same depths, and the principle part of the lower oxygen gradient ends at depths of 800 to 1000 meters.

Within the thermal convergences, lying just north of the principle convergence off Nova Scotia, all isolines in south north direction first slope downward and then upward (figs. 17, 18); these, for convenience, are termed second and third convergences respectively (page 59). Between the second and third convergences, at about latitude 40° 30′N, where all isolines reach a maximum dip the vertical distribution of oxygen and temperature is represented by station 1347. Here the main thermocline lies between approximate depths of 300 and 800 meters (17.5°–7.5°); the oxygen content above 300 meters is high and relatively uniform and then decreases from 4.8 cc per liter at that depth to a minimum of 3.5 cc at 600 meters, at 1500 meters it is more than 6.5 cc per liter. Within the third convergence all isolines are at a higher level and conditions are represented by station 1344 (41° 42′N, 64° 41′W). The main thermocline lies between 100 and 550 meters (13.5°–5.5°), the oxygen also decreases at the beginning of the thermocline from about 5.0 cc to about 3.2 cc per liter at 300 meters. The principle part of the lower oxygen gradient ends with a value of 6.2 cc per liter at about 1050 meters.

South of latitude 30°N the relationship of oxygen and temperature are illustrated by section B (figs. 5, 6, 7, 20) which, at the time of observation, showed an increase in winter surface temperature from 17.80° at its northern end (35°N) to 27.50° at 1°N in a distance of approximately 2000 nautical miles. As the annual range of temperature decreases between these latitudes from 8° in the north to 1° in the south (Schott, 1926) in summer the surface temperature would be more nearly uniform. Corresponding to the southerly increase of surface temperature we find in the water below the surface a convergence of isotherms toward the surface in a southerly direction (table 9). This condition, apparently resulting from an influx of cold southern water into the southern part of the section (page 5), causes the development of a strong discontinuity boundary which reaches its maximum stability where the cold water lies closest to the surface, i.e., at latitude 8°N (sta. 1174; figs. 5, 6; table 9). In effect the temperature gradient in the vicinity of latitude 8°N, near the 40th meridian, (sta. 1174 and neighboring stations) appears similar to an upwelling circulation, except that there is no reduction in surface temperature such, for instance, as occurs in the upwelling regions along the California coast (McEwen, 1912; Bigelow and Leslie, 1930), in the eastern Pacific (Moberg, 1930), and off the northwest coast of Africa (Schott, 1902). The prevailing high temperature of the surface water in this locality may result because warming of the surface water occurs at a greater rate than any upward movement of cold water. Any mixing which occurs between the thin warm surface layer and the colder water below (the result of turbulence developed by winds) apparently occurs at a rate so slow that it does not offset the effect of solar warming. The exact thickness of the homogeneous surface stratum at station

1174 is not known (observations were too far apart), but between surface and 43 meters the temperature decreased from 25.73° to 22.62°.

The following typical examples of the vertical oxygen and temperature distributions are representative for the eastern part of the region south of 30°N. Station 1166 (latitude 20° 50'N; fig. 7) is an example in which the correspondence between oxygen and temperature was good. The uniform temperature layer extended to a depth of approximately 75 meters (24.26°–24.10°) and the principle part of the thermocline reached to 1000 meters (5.7°); the oxygen content was uniform in the 0–75 meter layer (4.70–4.65 cc per liter, 97–95 per cent saturation) from which it decreased to a minimum value of 3.28 cc per liter, 49 per cent saturated, at 825 meters which is near the bottom of the thermocline.

Further south where the homogeneous temperature layer was thinner the correspondence with oxygen distribution was good also. Thus, at station 1170 (latitude 14° 47'N; fig. 7) where the uniform temperature layer extended to a depth of only about 50 meters (25.45°–25.30°), and the principle part of the thermocline to less than 600 meters (7.89° at 586 meters), the oxygen content at the surface was 4.65 cc per liter (96.5 per cent saturated) and at 100 meters had decreased to 4.56 cc per liter (92.4 per cent saturated) from whence it continued to decrease to a minimum of 1.73 cc per liter (26.8 per cent saturated) at 390 meters.

On the other hand, that the vertical distribution of oxygen and temperature in the upper layers do not always correspond well is indicated by conditions at station 1178 (2° 2'N; figs. 7, 20) where the uniform temperature layer extended to a depth of about 50 meters (27.0°–26.6°) and the principle part of the thermocline to about 400 meters (6.54° at 366 meters). The oxygen content was relatively uniform to a depth of 140 meters, 4.47–4.55 cc per liter (95–88 per cent saturated) from

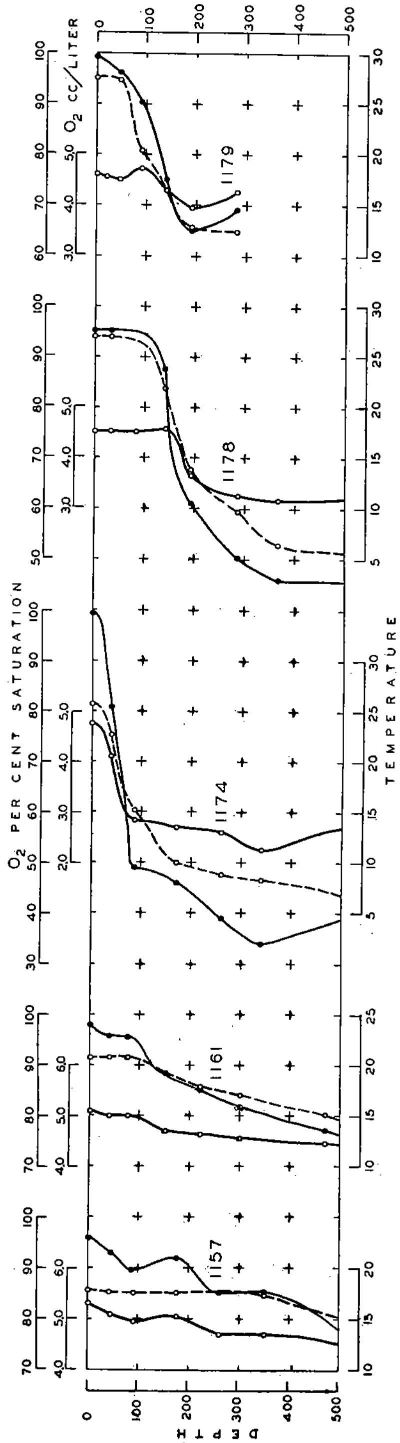

FIG. 20.—Vertical distribution of oxygen (per cent of total saturation and cc per liter) and temperature 0–500 meters at "Atlantis" stations 1157 (35° 10'N, 44° 40'W, March 3–4, 1932); 1161 (28° 38'N, 41° 57'W, March 7, 1932); 1174 (8° 20'N, 40° 45'W, March 16–17, 1932); 1178 (2° 2'N, 41° 18'W, March 20, 1932); 1179 (0° 45'N, 42° 38'W, March 21, 1932).

whence it decreased rapidly to a minimum of 3.17 cc per liter (46 per cent saturated) at 366 meters.

Thus, the relationship of oxygen and temperature distribution is of particular interest in the southern part of the region where the homogeneous thermal layer is very thin because, here, the thermocline involves part of the layer where photosynthesis takes place and, in cases where the rich oxygen layer reaches downward into the thermocline, may furnish evidence of the approximate depth to which an intense photosynthesis commonly occurs. We see this condition at stations 1178 and 1179 (fig. 20) where the uniformly warmed surface layers extend to depths of about 50 meters but where high concentrations of oxygen extend to 140 and to 90 meters respectively. At station 1178 the temperature decreased from 27.05° at the surface to 21.76° at 140 meters whereas the absolute oxygen content actually increased 4.49 to 4.55 cc per liter (95 to 88 per cent saturated). At station 1179, the temperature decreased from 27.50° at the surface to 20.35° at 93 meters, but with an increase in absolute oxygen from 4.61 to 4.72 cc per liter (99 to 90 per cent saturated).

However, other stations in the same general region show the warm and the highly oxygenated layers as about equal in thickness. Thus, for example, at station 1174 (fig. 20; latitude 8° 20′N), very pronounced oxygen and temperature gradients were developed well within the 100 meter layer, temperature decreasing from 25.73° at the surface to 13.75° at 100 meters, and the oxygen from 4.76 to 2.82 cc per liter (99 to 48 per cent saturated). Similarly, at the neighboring stations, 1173 (9° 57′N) and 1175 (6° 50′N), the temperature decrease, 0 to 100 meters, was 25.64° to 17.3° and 27.08° to 23.0° respectively, while the oxygen decreased 4.72 to 3.39 cc per liter (98 to 67 per cent saturation) and 4.49 to 3.56 cc per liter (96 to 80 per cent saturation).

The simultaneous development of strong oxygen and temperature gradients, as at the above three stations, even when the homogeneous water is confined to a very thin surface layer (less than 40 meters at station 1174; fig. 20), suggests that, at this particular locality, photosynthesis was confined mainly to this small depth. This may be the result of poverty of species of vegetable plankton that are able to live within the strong thermocline and of decrease in metabolism per unit because of decreased temperature. For example, at station 1174, the temperature difference of more than 12° between surface (27.73°) and 86 meters (15.11°) would suggest that at the latter depth the rate of metabolism per unit would be approximately one-half of the rate at the surface. On the other hand it is entirely possible that an active photosynthesis may extend into the upper part of the thermocline as is indicated for stations 1178 and 1179 but that in the case of station 1174 and the neighboring stations there is a balance existing between the rate at which the water is oxygenated by photosynthesis and the rate at which oxygen poor water is carried up, so that the effect of the photosynthesis is offset. Available data are not sufficient for a more definite conclusion.

Further west in the region south of Bermuda, as indicated by section C (figs. 8, 9), in the early spring of 1933 the homogeneous temperature layer was generally not more than 50 meters thick and frequently the temperature gradient began almost at the surface (fig. 10). Evidence of photosynthetic activity in the surface layer is indicated either by an increase in oxygen below the surface, or by extension of the uniform oxygen layer down to depths of 50 to 200 meters in spite of the temperature gradient.

Relationship to Stability of the Water Column

The distribution of stability along a north south line in the region of investigation may be illustrated by conditions in "Atlantis" section B. With the increased temperature the density of the surface water in general decreased from north to south, in units of σ_t from 26.48 to 23.13. Paralleling the development of lighter surface water the decreased temperature of subsurface water (page 34) produces an opposite condition and there is an increase in density of the water lying immediately below the surface. Thus, the upper water layers are much more stable in tropical latitudes than in the Sargasso Sea region, the difference in stability between surface and 75 meters usually being from 0 to $0.05\sigma_t$ units at the northern part of the section, increasing in tropical latitudes to 1.93 σ_t units.[6] Thus, the transport of oxygen into the subsurface layers by turbulence is for the time of observation less in tropical waters than in the Sargasso Sea region to the north. Particularly is this apparent when we consider oxygen transport into the upper part of the oxygen poor layer, for, in spite of the fact that the distance from the surface down to the isoline of 60 per cent saturation of oxygen is much less in the tropics than in the Sargasso Sea region, the vertical stability may be twenty-five times as great.[7]

Thus, the differences in vertical oxygen distribution between northern and southern latitudes, no doubt, depend to a great extent on the distribution of stability in the water column. For the midstratum, where large amounts of oxygen are consumed by organic oxidations, the development of boundary surfaces in the overlying water, by decreasing the oxygen supply from above, causes the supply to depend more on horizontal currents. The result is not only to decrease the minimum oxygen concentrations, but to increase the vertical thickness of the oxygen poor layer.

The internal stability of the oxygen poor layer is low and fairly uniform throughout section B, the average downward increase of σ_t per linear meter varied between 0.00052 and 0.00187, the average maximum stability of any vertical section within it was only 3.6 times greater than the average minimum.

In general, organic debris of uniform specific gravity would, from the vertical distribution of density or stability of the water column, sink into deeper water before entirely decaying in northern latitudes than in southern. This consideration together with the decreased oxygen supply from the surface layer appears to be in part responsible for the surfaceward expansion of the oxygen poor layer in tropical latitudes.

Further west the distribution of stability in the water south of Bermuda is illustrated by conditions in section C. Since the density in units of σ_t of the surface water decreased from 26.34 near Bermuda to 24.06 in the south, and the σ_t of the upper boundary of the oxygen poor layer (isoline of 60 per cent relative saturation) varied from 26.88 to 27.18, it follows that here also more stable water is present in the southern part of the region. If we express the approximate stability as the change of σ_t per linear meter the variation is from 0.000928 in the north to 0.00578 in the south, i.e., the stability of the water above the oxygen poor layer is approximately 6.3 times as great in the southern part of the region as near Bermuda.

West of Bermuda the distribution of stability is illustrated by conditions in section E.

[6] For a comparison between stability conditions in different regions it is sufficient to consider the change with depth of σ_t.

[7] Estimating the stability of the water column lying between minimum layer and the surface (upper oxygen layer) we find that at latitude 32° the stability expressed as units of σ_t per linear meter is 0.00107 while at latitude 8° a stability of 0.0268 σ_t units per linear meter, or 25 times as great is attained.

The density, σ_t, of the surface water ranged from 24.88 to 26.36 and that of the upper boundary of the oxygen poor layer from 26.62 to 27.12. The stability of the water overlying the oxygen poor layer (upper oxygen layer) represented as before by the change in σ_t per linear meter was 0.00082 to 0.00145 units for the region east of the thermal convergence; (longitude 72° 47′W) and 0.0055 to 0.0077 units for the region west of the thermal convergence (longitude 73° 05′W). Thus, the stability of the upper oxygen layer west of the convergence is 5 to 6 times greater than it is to the east. The density (σ_t) of the lower boundary of the oxygen poor layer was, in spite of the change of level, practically uniform throughout the section, 27.34 to 27.50 units. It is probable that west of the thermal convergence the great mass of organic oxidations occur at higher horizontal levels than is the case in the water east of the convergence. Here again the stability conditions appear to be in large part responsible for the position and the thickness of the oxygen poor layer in the water column.

Comparing the stability conditions existing in the water overlying the oxygen poor layer of section E with that of section B we find that between Bermuda and the thermal convergence (to longitude 72° 47′W) the stability expressed as 0.00082 to 0.00145 σ_t units per meter is of the same magnitude as that characterizing the upper layer in the northern part of section B.

Seasonal Variation

Because of the distribution of stability in the area under investigation and of the fact that the amplitude of the annual temperature variation of the surface waters decreases from north to south (page 34), it is only in the northern part of the region of investigation that seasonal changes in the oxygen content resulting from seasonal temperature variation appear to be significant. A comparison of winter and summer conditions shows only small seasonal differences in the oxygen content of the water of the northeastern Sargasso Sea near station 1152 (34° 48′N, 55° 30′W) and 1157 (35° 10′N, 44° 40′W; fig. 4). The principle seasonal changes are confined to the surface layer and correspond to the summer development of a boundary surface in the upper 100 meters due to a rise in surface temperature from 17.8° to 25.1°. This boundary surface may be expected to restrict convectional circulation which in winter may extend to a depth of 400–500 meters so that in summer a maximum of oxygen content, no doubt the result of photosynthesis, occurs at 50 meters. The oxygen minimum lying at depths of 800 to 1000 meters has practically the same amount of oxygen (about 4.0 cc per liter) both in summer and winter.

Whereas complete saturation is recorded frequently for the surface layers of the ocean, at the time of observation the oxygen content of the surface stratum of section A was usually only 90–95 per cent saturated with oxygen (table 1). This is apparently the result of winter conditions when the lowered temperature of the surface layers increased the saturation power of the water and the additional oxygen required for complete saturation had not yet accumulated. The time required for the surface layer of the ocean to become saturated with oxygen after its temperature has been lowered seems, in the light of present knowledge, to depend on the activity of the photosynthetic processes and on the strength of the winds. If the surface temperature at, for instance, station 1157 was raised from its winter value of 17.8° to its summer value of 25° with no change in winter oxygen content (5.29 cc per liter) the oxygen saturation would be raised considerably above 100 per cent.

In the water between Bermuda and the American coast the seasonal variation of oxygen can be illustrated by observations obtained during the four quarterly cruises of "Atlantis" over that route in 1932. Two groups of stations east of the thermal convergence (longitude 72° 47'W on section E), centering around stations 1221 and 1226, are selected for the analysis. The first group includes station 1144 (33° 34'N, 66° 29'W), February 17,

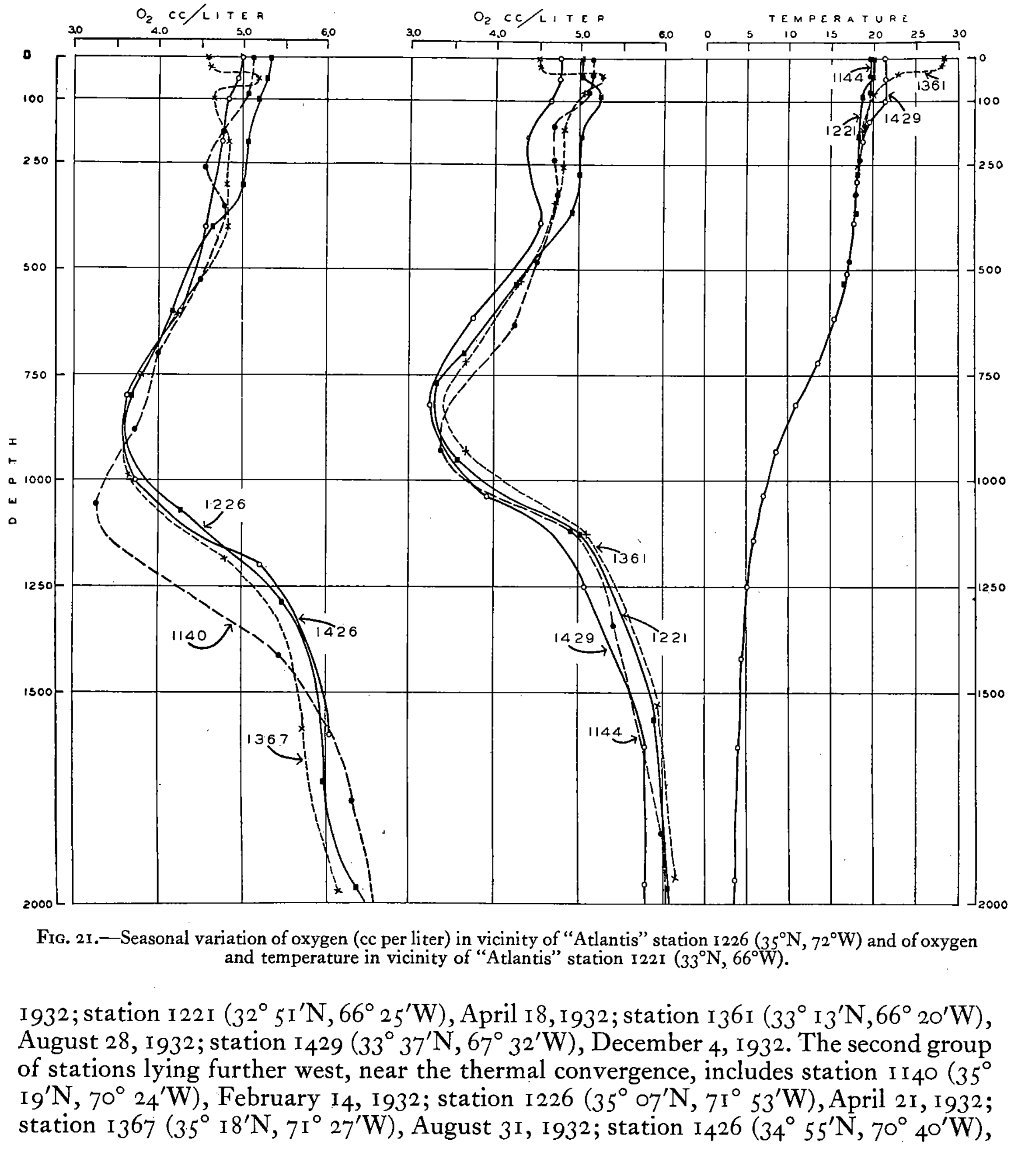

FIG. 21.—Seasonal variation of oxygen (cc per liter) in vicinity of "Atlantis" station 1226 (35°N, 72°W) and of oxygen and temperature in vicinity of "Atlantis" station 1221 (33°N, 66°W).

1932; station 1221 (32° 51'N, 66° 25'W), April 18, 1932; station 1361 (33° 13'N, 66° 20'W), August 28, 1932; station 1429 (33° 37'N, 67° 32'W), December 4, 1932. The second group of stations lying further west, near the thermal convergence, includes station 1140 (35° 19'N, 70° 24'W), February 14, 1932; station 1226 (35° 07'N, 71° 53'W), April 21, 1932; station 1367 (35° 18'N, 71° 27'W), August 31, 1932; station 1426 (34° 55'N, 70° 40'W), December 2, 1932. The seasonal distribution of oxygen for each group and the seasonal distribution of temperature for the eastern group (sta. 1221) are plotted in figure 21.

Significant seasonal temperature variations in this region appear to cease at about 200 meters depth (fig. 21); near station 1221 the surface temperature decreased from 28.4° at the end of August to 21.4° by the beginning of December which was sufficient to break down the upper or summer thermocline, this allowing a complete mixing of the upper 100 meter layer. By the middle of February the surface temperature had declined to less than 20° and the depth of the convectional mixing increased, the temperature gradient between surface and 400 meters was only 2° approximately. The February surface temperature is probably close to the minimum for the year and the water column remains in this not very stable condition until after the middle of April.

Correlated with these seasonal temperature changes, our records indicate an oxygen variation for the surface water west of Bermuda of 4.5 to 5.3 cc per liter. The lowest absolute values, 4.49 cc per liter at station 1361 and 4.59 cc per liter at station 1367, occur in summer when the surface temperature is highest (27°–28°), while the highest absolute values, 5.14 cc per liter at station 1144, 5.34 cc per liter at station 1226, occur when surface temperatures are lowest (<20°C). The relative saturation generally remains above 96 per cent throughout the year except that at station 1429 on December 4 it had dropped to 92 per cent. This, however, appears to have been only a temporary condition, perhaps resulting from a drop in temperature so sudden that the surface water had not yet accumulated enough additional oxygen to take care of the increased capacity for the dissolved gas.

In the water immediately below the surface in this region the summer development of a boundary surface within the 100 meter level, shown by the August observations, limits convectional circulation, and a maximum of oxygen content occurs in the vicinity of 50 meters depth (5.27 cc per liter, 104 per cent saturated, at station 1361; 5.19 cc per liter, 103 per cent saturated, at station 1367). From the end of the summer until the following late spring the oxygen released by photosynthesis is distributed throughout the upper layers and no permanent oxygen gradient exists between 400 meters and surface. At station 1221, April 18, an oxygen maximum, 5.25 cc per liter, 97 per cent saturated, existed at about 100 meters depth but is apparently only a temporary condition resulting from a temporary stabilization of the overlying water for at station 1226, three days later, this maximum is absent.

Thus, the most significant seasonal variations of oxygen content are confined to depths less than 100 meters. In the water column between the two thermoclines (100–400 meters) an approximate uniformity exists throughout the year; for both groups of stations it is apparent from figure 21 that the seasonal variations of oxygen below 100 meters are of no greater magnitude than individual differences existing for the water west of the Bermuda Islands for any particular time such as would be caused by horizontal movements of the water. In discussing the horizontal variation of oxygen in depths below 100 meters seasonal variations as caused by convectional circulation induced by winter cooling can be neglected.

Summary of the Characteristics of the Oxygen Poor Layer

Regional differences in vertical distribution of oxygen have been discussed previously by dividing the whole water column into three oxygen layers based on the position of the 60 per cent isoline of relative saturation (page 8). Of particular importance is the oxygen poor layer (wherein the oxygen content is less than 60 per cent of total saturation) which, occupying the midstratum of the water column (figs. 22, 23, 24), is dependent principally upon horizontal currents for its oxygen supply. On the other hand, in the overlying water, which includes the layer of photosynthesis, reoxygenation is taking place continually so that for the most part evidence of organic oxidations resulting from plant and animal respiration and the decay of carcasses is masked. In the water below the oxygen poor layer relative saturation is again high (greater than 60 per cent of total saturation) and the supply of oxygen comes principally from horizontal currents, but the relative rate of oxygen utilization is apparently much slower than in the overlying water. Thus, the thickness and position of the oxygen poor layer in the water column gives evidence of the relative amounts of oxygen present in the various parts of the region and the approximate limits to which most of the organic oxidations occurring in the sea are confined (page 83).

While the range of thickness of the oxygen poor layer is great (0 to 1200 meters) definite thickness gradients characterize the various parts of the region under investigation (fig. 23). Thus, in north south direction along the 40th meridian (section B, fig. 6) the thickness increase was from 0[8] near latitude 35°N to 1100–1200 meters between latitudes 16° and 2°N. Further west, near the longitude of Bermuda, in north south direction the thickness of the oxygen poor stratum in the thermal convergences off Nova Scotia ranges between 100 and 300 meters while south of latitude 38°N the layer in general is 200–400 meters thick increasing to more than 500 meters south of latitude 18°N (section C, fig. 9).

In east west direction, along latitude 35°N, the width of the oxygen poor layer increases from 0 at longitude 35°W to more than 300 meters within a short distance. Westward from the longitude of Bermuda the thickness of this layer decreases slowly to less than 200 meters; within the thermal convergence the decrease is rapid and the layer actually disappears for a short distance.[9] West of the convergence the thickness of the oxygen poor layer rapidly increases again to 300 meters (figs. 15, 23).

The thickness of the oxygen poor layer bears certain definite relationships to the depth of its upper boundary, which in the region of investigation lies between 75 and 900 meters (fig. 22). Thus, in north south direction along the 40th meridian with increasing thickness the depth of the upper boundary decreases from 600–800 meters north of 25°N to less than 200 meters between latitudes 16° and 2°N at which place also occurred the maximum thickness. A minimum depth of 75 meters characterizes the upper boundary at 8°N (fig. 6).

From east to west across the north central part of the region, as far as the thermal

[8] The absence of oxygen poor layer from a small portion of the northeastern part of the region is based on observations at "Atlantis" stations 1155, 1157, and 1158. This is one of two areas where the minimum oxygen values in the vertical column did not fall below 60 per cent.

[9] The absence of the oxygen poor layer in the thermal convergence off Chesapeake Bay (between longitudes 72° 53′W and 73° 00′W, in section E, fig. 16) is the second of the two cases in which the minimum oxygen values do not fall below 60 per cent of total saturation. In this case it is suggested that an enrichment of oxygen occurs in the thermal convergence at the depths at which the minimum contents would normally occur resulting from eddy transport induced by the strong horizontal currents.

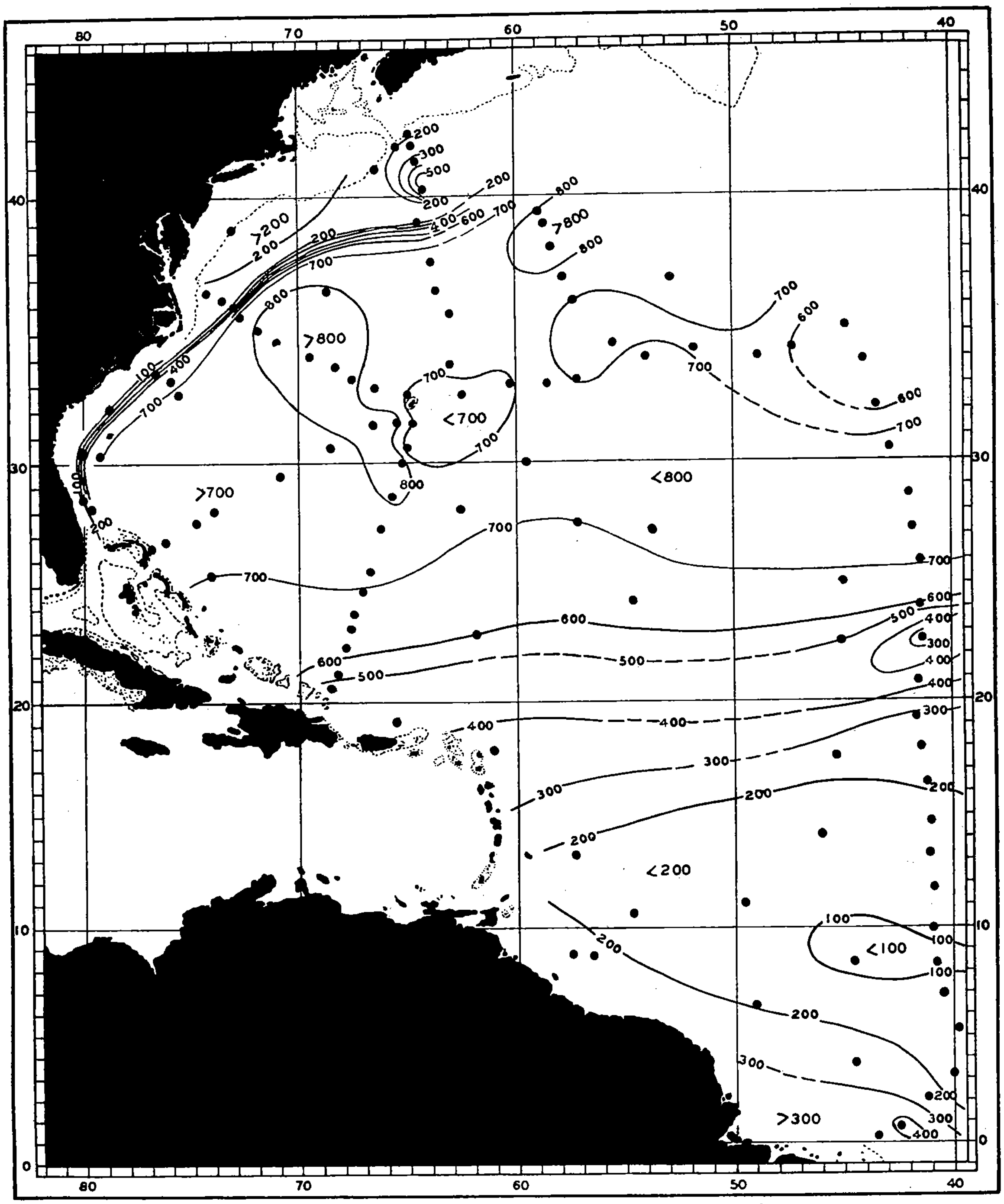

FIG. 22.—Depth of upper boundary (upper sixty per cent of total saturation isoline) of oxygen poor layer in area of investigation.

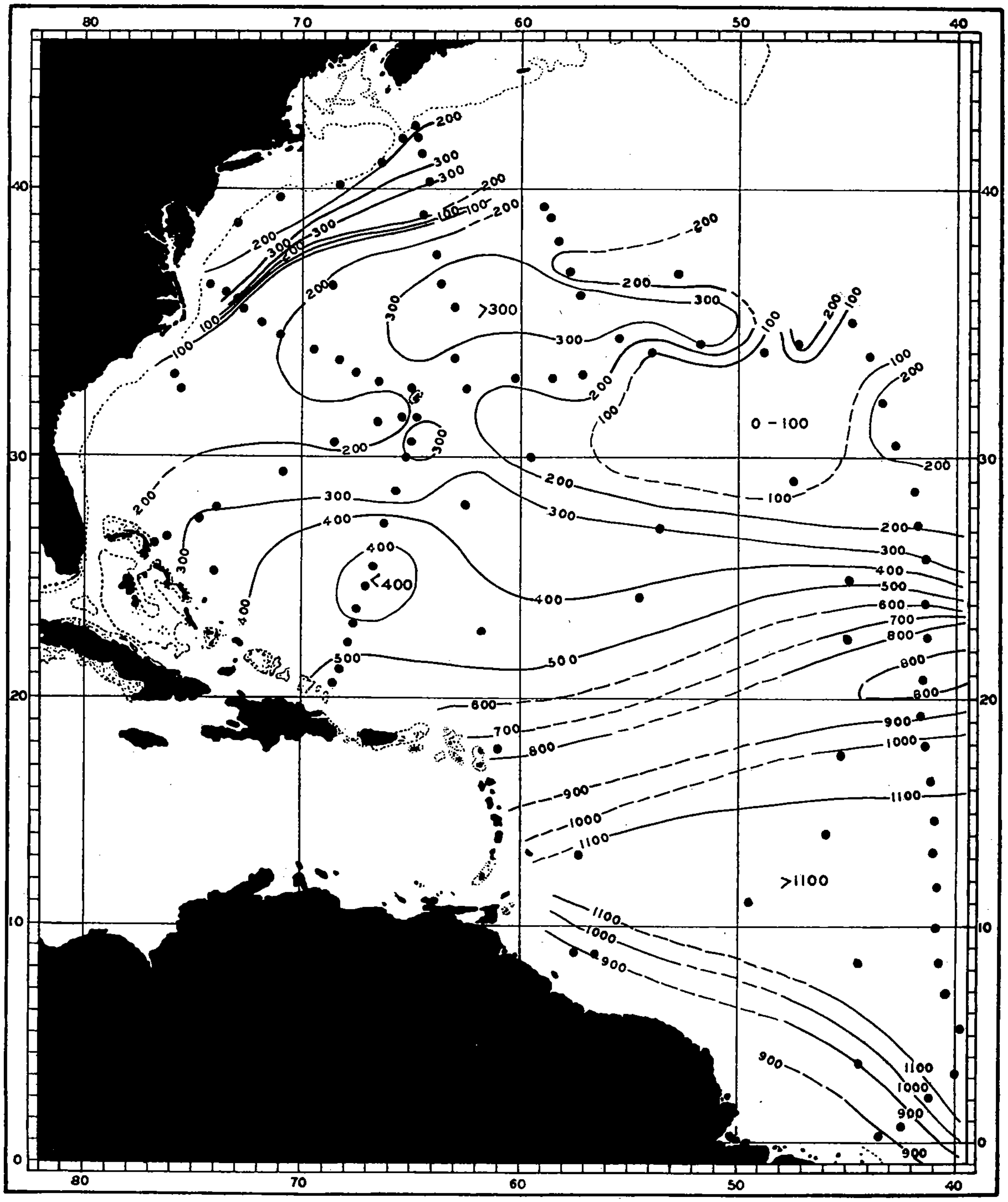

FIG. 23.—Thickness of oxygen poor layer in area of investigation.

convergence, the depth of the upper boundary lies generally between 600 and 800 meters corresponding to a relative constant thickness of the oxygen poor layer, while within the thermal convergence as the oxygen poor layer thins the upper boundary rises rapidly surfaceward from 600 to less than 200 meters (page 27). West of the convergence the upper boundary continues to lie at about 200 meters depth as the oxygen poor layer increases in thickness (fig. 15). A similar relationship of thickness and depth of the oxygen poor layer occurs in the most southerly thermal convergence off Nova Scotia where the upper boundary of the oxygen poor layer decreased in depth from more than 600 to less than 200 meters (page 31) and the thickness decreased to less than 100 meters (fig. 18).

Thus, while the decrease in depth of the upper boundary of the oxygen poor layer in all cases corresponds to an increased density of the water between it and the surface the relationship of depth of this boundary to thickness of the oxygen poor layer is the reverse in the thermal convergences off the American coast to what it is in the thermal convergence of tropical waters (see page 16). This condition in the western North Atlantic is perhaps the result of differences in horizontal circulation on which the oxygen supply of the water below the 60 per cent isoline is dependent principally.

HORIZONTAL DISTRIBUTION OF OXYGEN

General Distribution

Combination of the values along the several "Atlantis" sections with other available data has allowed the construction of the accompanying charts of horizontal distribution at different depths (figs. 25 to 36).

Surface.[10] The distribution of relative oxygen content at the surface is more uniform than at deeper levels, being invariably above 90 per cent of total saturation in the region under discussion and generally close to complete saturation. Variations in the relative oxygen content are probably local and of temporary duration which result from diurnal variation in biochemical factors or from sudden changes in the temperature of the water. Variations in absolute oxygen values follow the surface temperature variations, the maximum range (6.6 cc to 4.5 cc per liter) over the area occurring in winter and the minimum in summer (page 38). In section B (fig. 6) absolute values decreased from 5.32 cc in the north to 4.49 cc per liter in the south, paralleling a temperature rise in the same direction of 17.7° to 27.5°. With less of a north south temperature range in summer the range of absolute oxygen values decreases. An example of this is illustrated by station 1226, lying between Bermuda and Chesapeake Bay, which shows an annual variation of absolute oxygen from 5.34 cc per liter in winter to 4.59 cc in summer corresponding to a temperature variation from about 20° to 28° (fig. 21; page 40), the summer values being close to those which characterize tropical waters throughout the year.

In the region of investigation there are no circumscribed pools with low oxygen content such as would suggest that oxygen poor water from below had welled up; phenomena such as have been reported recently for the Pacific (Moberg, 1930) and Antarctic (Deacon, 1933).

Subsurface. Descending below the surface, seasonal variations decrease and regional variations become more pronounced. Thus, at 100 meters (figs. 25, 26) the seasonal varia-

[10] Due to the small magnitude of the regional variation of relative oxygen content at the surface, and the fact that absolute values depend principally on seasonal temperature variations no chart showing the distribution of oxygen at this level has been prepared.

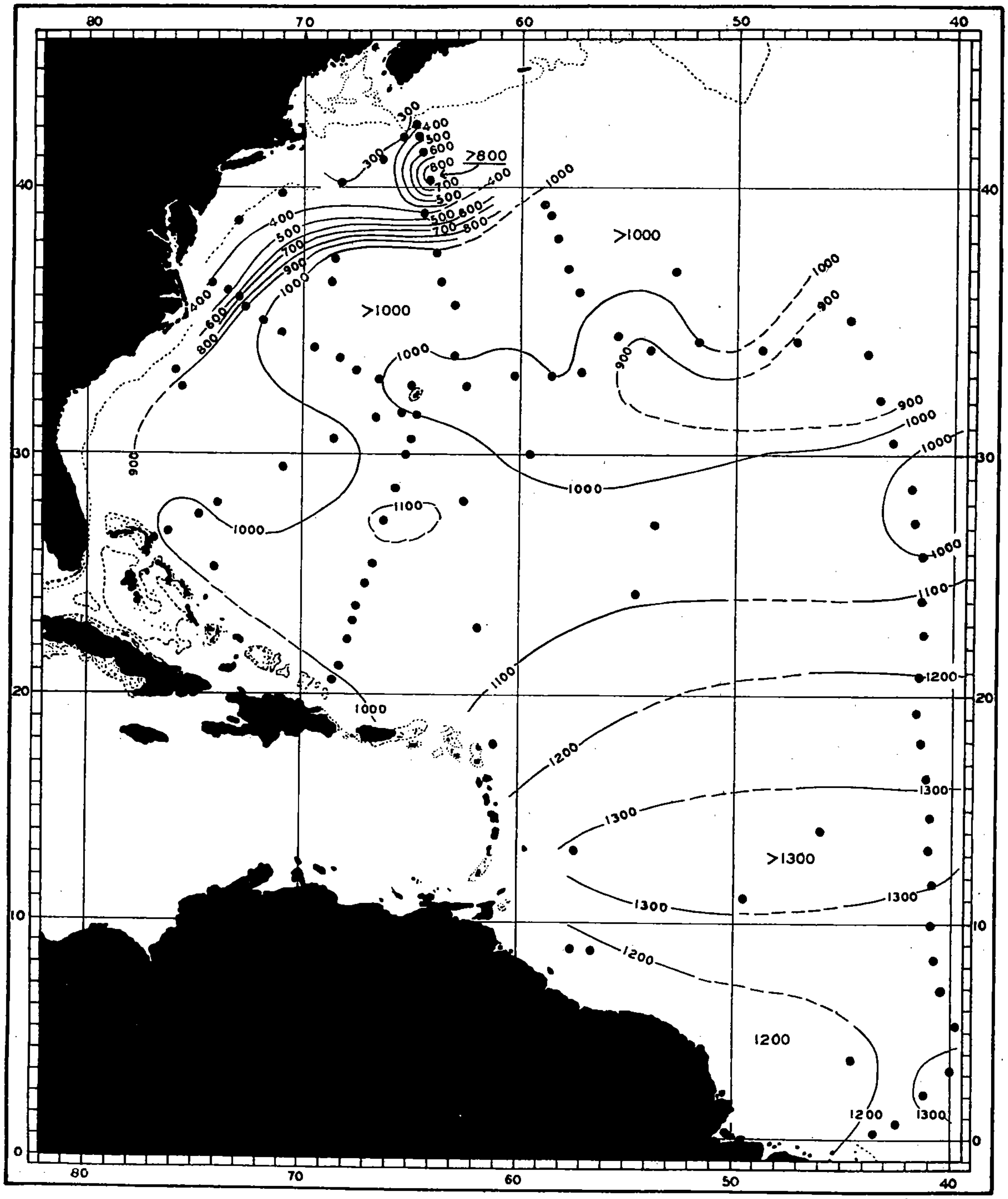

FIG. 24.—Depth of lower boundary (lower sixty per cent of total saturation isoline) of oxygen poor layer in area of investigation.

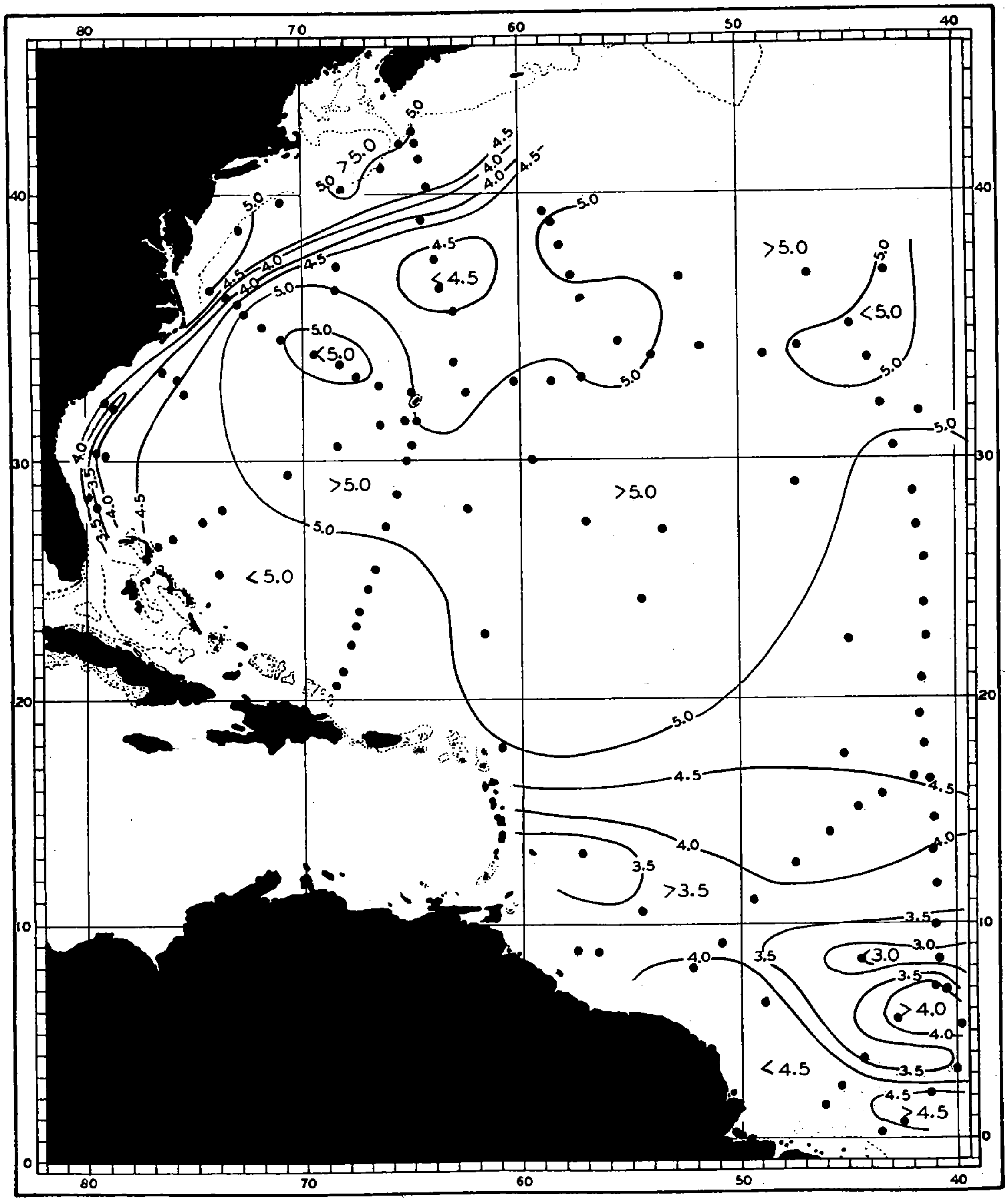

FIG. 25.—Horizontal distribution of oxygen (cc per liter) at 100 meters depth.

tion even in northern parts of the region apparently seldom exceeds 0.5 cc per liter (page 38). In general at this depth photosynthesis and nearness to the atmosphere tend to bring about a uniformity in oxygen content, but in the thermal convergences along the American coast and in the trade wind region there occur great reductions in oxygen content, corresponding to temperature reductions, which are lower than might be considered normal for the region. Thus, while the total horizontal variation of oxygen at 100 meters is 2.7 to 5.4 cc per liter and from 48 to 100 per cent saturation, the greater part of the region which lies east and north of the convergences is in general characterized by values of 4.5 to 5.2 cc per liter, 90 to 100 per cent saturation.

Because of vertical circulation in the northern part of the region the 250 meter level (figs. 27, 28) may be subject to small seasonal variation in absolute oxygen content (page 38). The variation in oxygen at this depth is similar to that for 100 meters, the lowest values occurring in the thermal convergences. The total horizontal variation is from 2.3 to 5.1 cc per liter, 37 to 92 per cent of total saturation, but, within the north central part of the region, east and north of the convergences, the oxygen usually varies from 4.5 to 5.1 cc per liter.

In the deeper water at 500 meters depth (figs. 29, 30) the oxygen content is more dependent for its renewal on horizontal currents, and variations are due principally to the age of the water and the distribution of density in the overlying water (page 40). The total horizontal variation at this depth varies from 2.3 to 4.6 cc per liter, 29 to 83 per cent saturation, the lowest values occur in the thermal convergences. In still deeper water at 1000 meters (figs. 31, 32) oxygen varies from 3.1 to 6.2 cc per liter, 43 to 86 per cent saturation, the higher oxygen contents occur in the thermal convergences off the American coast and the minimum in the thermal convergence of the equatorial region. At 1500 meters (figs. 33, 34) the variation is smaller being 4.6 to 6.4 cc per liter, 67 to 87 per cent saturation; and in the deeper water at 2500 meters (figs. 35, 36) the range is only from 5.4 to 6.3 cc per liter, 73 to 85 per cent of total saturation. In the water deeper than 1500 meters we note that the absolute oxygen content may be more than 1 cc per liter higher than it is at the surface but the relative oxygen content is lower. This condition is presumably due to the fact that the water filling the deepest parts of the ocean originates at the surface of high latitudes where, under low temperature conditions, it has a greater saturation power for oxygen than has the water of temperate or tropical latitudes. Hence, if at the time of its sinking from the surface it was saturated totally with oxygen it would have contained at the outset considerably more oxygen than the much warmer surface water of lower latitudes, and as the water filling the deeper parts of the ocean is removed from processes of areation for long periods of time it slowly loses its oxygen which is expressed by the lower relative saturation.

North South Distribution

Distribution in the eastern part of the area is illustrated by section B, near the 40th meridian (figs. 5, 6). In general the iso-oxygen lines in the meridional thermal convergence follow the trend of the isotherms though the correlation is not as definite as in the region of the American coastwise convergences (page 56). All isotherms existing between the surface and 10° isotherm and all isolines of oxygen existing between the surface and 50 per cent relative saturation isoline (about 3.0 cc per liter) have approximately the same slope (figs. 5, 6). These isotherms and iso-oxygen lines occupy the water column

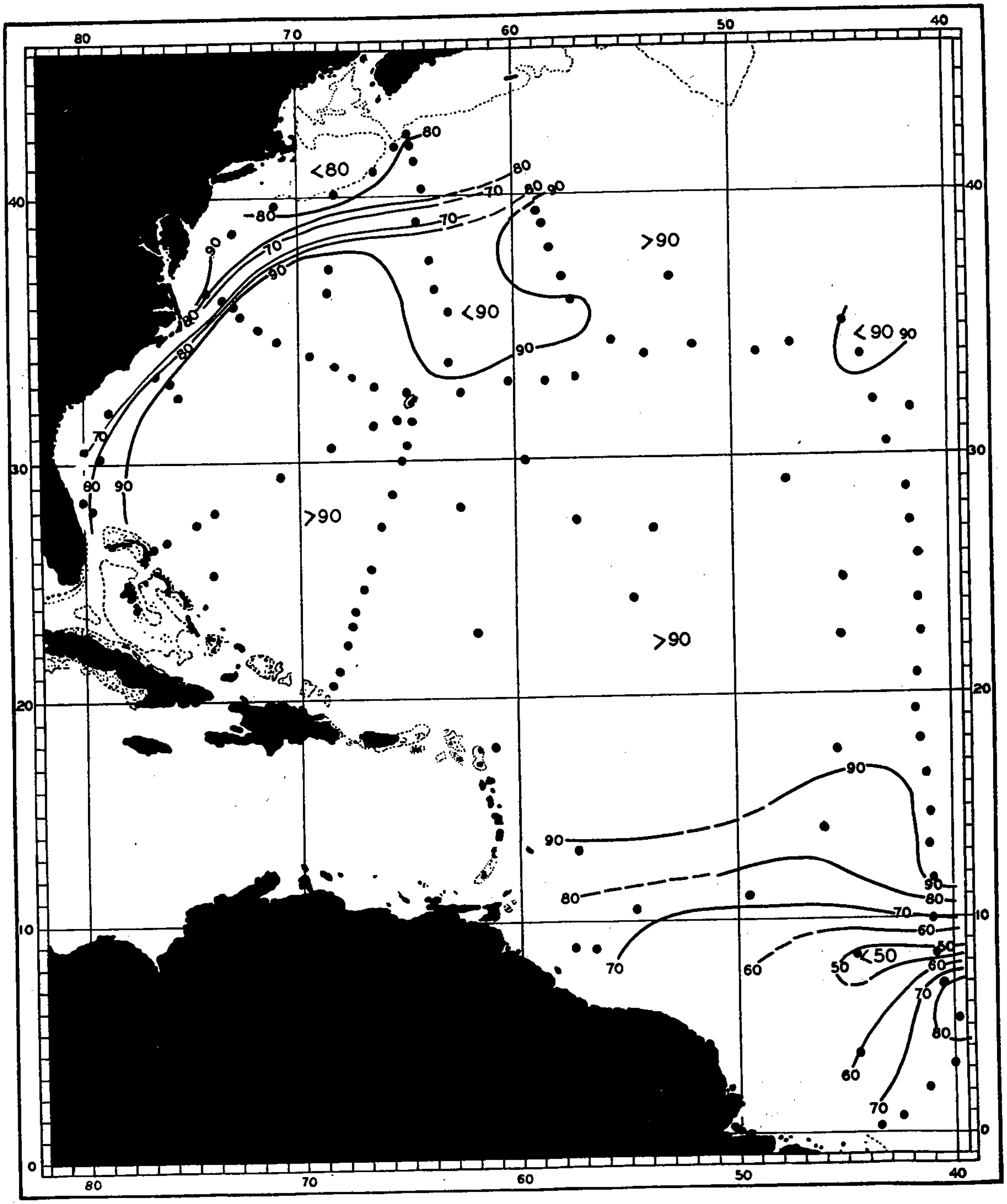

FIG. 26.—Horizontal distribution of oxygen (per cent of total saturation) at 100 meters depth.

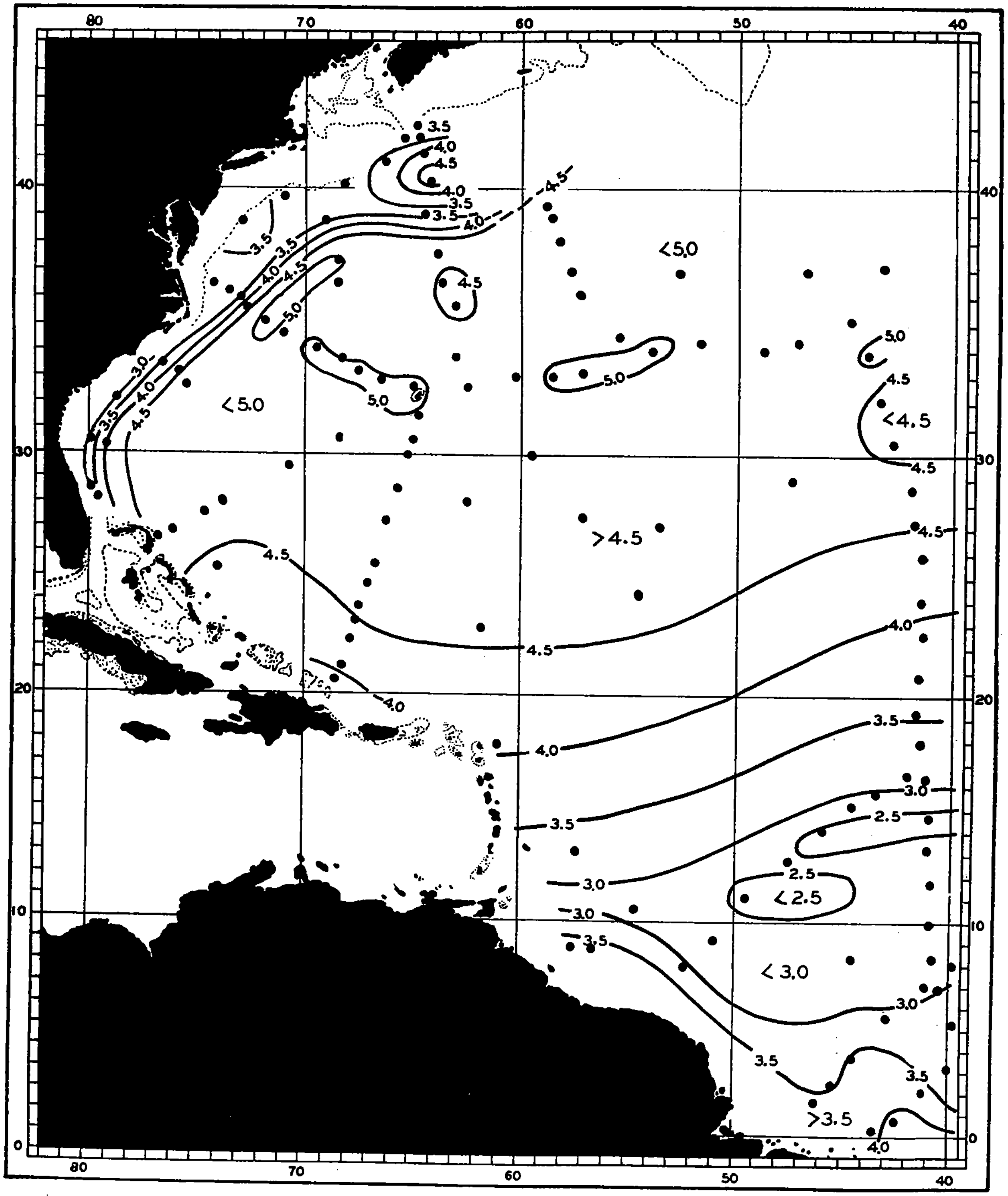

FIG. 27.—Horizontal distribution of oxygen (cc per liter) at 250 meters depth.

down to 800–900 meters in the northern part of the section but only to 200 meters in the vicinity of 8°N latitude; to the south of which they run either closely horizontal or again dip slightly.

The north south distribution of oxygen at the surface has been discussed previously (page 44). In the underlying water the horizontal variation increases and maximum concentrations at all levels of section B are found at the northern part, the minimum concentrations occurring between latitudes 16° and 8°N (sta. 1169–1174). Variations at different levels in this section are illustrated in table 10.

TABLE 10

Depth	O_2 cc/liter	Variation cc/liter	O_2 Per Cent Saturation	Variation per cent	Latitude of Minimum
100	5.2–2.9	2.3	95–49	46	8°20′
250	5.0–2.6	2.4	90–39	51	8°20′
400	4.6–1.7	2.9	83–27	56	14°47′
500	4.5–2.1	2.4	78–31	47	14°47′
750	4.3–2.5	1.8	70–36	34	11°43′
1000	4.8–3.0	1.8	69–42	27	14°47′
1500	5.8–4.9	0.9	78–67	11	11°43′
2500	6.0–5.4	0.6	80–73	7	16°22′

The north south oxygen distribution in the upper part of the water column may be illustrated by the situation existing at 100 meters (figs. 25, 26) where a prominent horizontal gradient is developed in tropical latitudes with the oxygen decreasing along the 40th meridian from almost 4.0 cc per liter near latitude 11° 30′N to 2.8 cc per liter at latitude 8° 30′N and then increasing southward to 4.5 cc per liter at latitude 5° 30′ N (90 to <50 to 80 per cent saturation). At this depth the lowest oxygen concentrations occur where the coldest water lies nearest the surface and horizontal oxygen variations are due primarily to the upward movement of cold water poor in oxygen.

Descending below 100 meters the coldest water at any horizontal level occurs at latitude 8°N or further south (fig. 6), but at depths where the water is characterized by a temperature of less than 10° or an oxygen content less than 50 per cent of total saturation, the oxygen poorest water for that level occurs north of latitude 8°N (table 10). Hence, at 250 meters depth (figs. 27, 28) oxygen decreased from almost 4.5 cc per liter (80 per cent saturated) at latitude 25°N to 3.0–2.5 cc per liter (50–40 per cent saturated) between latitudes 16° and 7°N, and then increased gradually to 4.0 cc per liter (60 per cent saturated) near the equator. At this depth the location of the horizontal oxygen minimum is somewhat north of the coldest water and is the combined result of the oxygen content within the oxygen poor layer and the effect of the thermal convergence (fig. 6). The minimum oxygen concentration of section B occurs at 400 meters depth near latitude 15°, and at this depth also is found the maximum horizontal variation for the whole water column (4.6 to 1.7 cc per liter, 83 to 27 per cent saturated, table 10). At 500 meters depth (figs. 29, 30) the convergence has loosened somewhat, the plane intersects the oxygen poor layer south of latitude 23°N and is also below the minimum oxygen concentrations which occur between the latitudes of 16° and 7°N (representing the lowest oxygen values in section B; figs. 5, 6). Hence, the horizontal variation is less than at 400 meters (table 10). In the principle north south gradient the oxygen decreased from 4.0 cc per liter (68 per cent saturated) at latitude 26°N to less than 2.5 cc per liter between 19° and 9°N (<40 per cent saturated) then increased toward the south to about 3.5 cc per liter (50 per cent saturated). The minimum oxygen values at this level occurred where

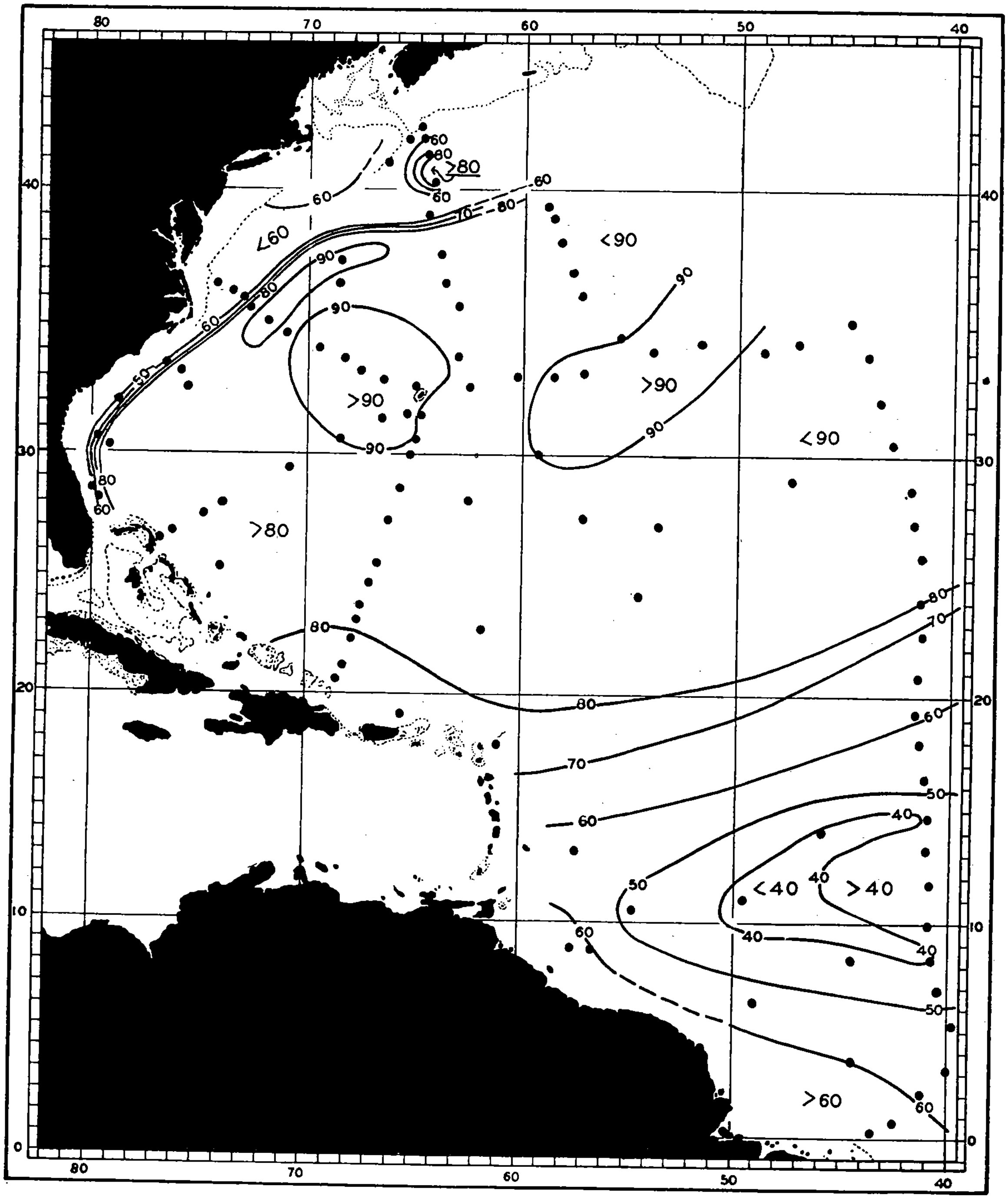

Fig. 28.—Horizontal distribution of oxygen (per cent of total saturation) at 250 meters depth.

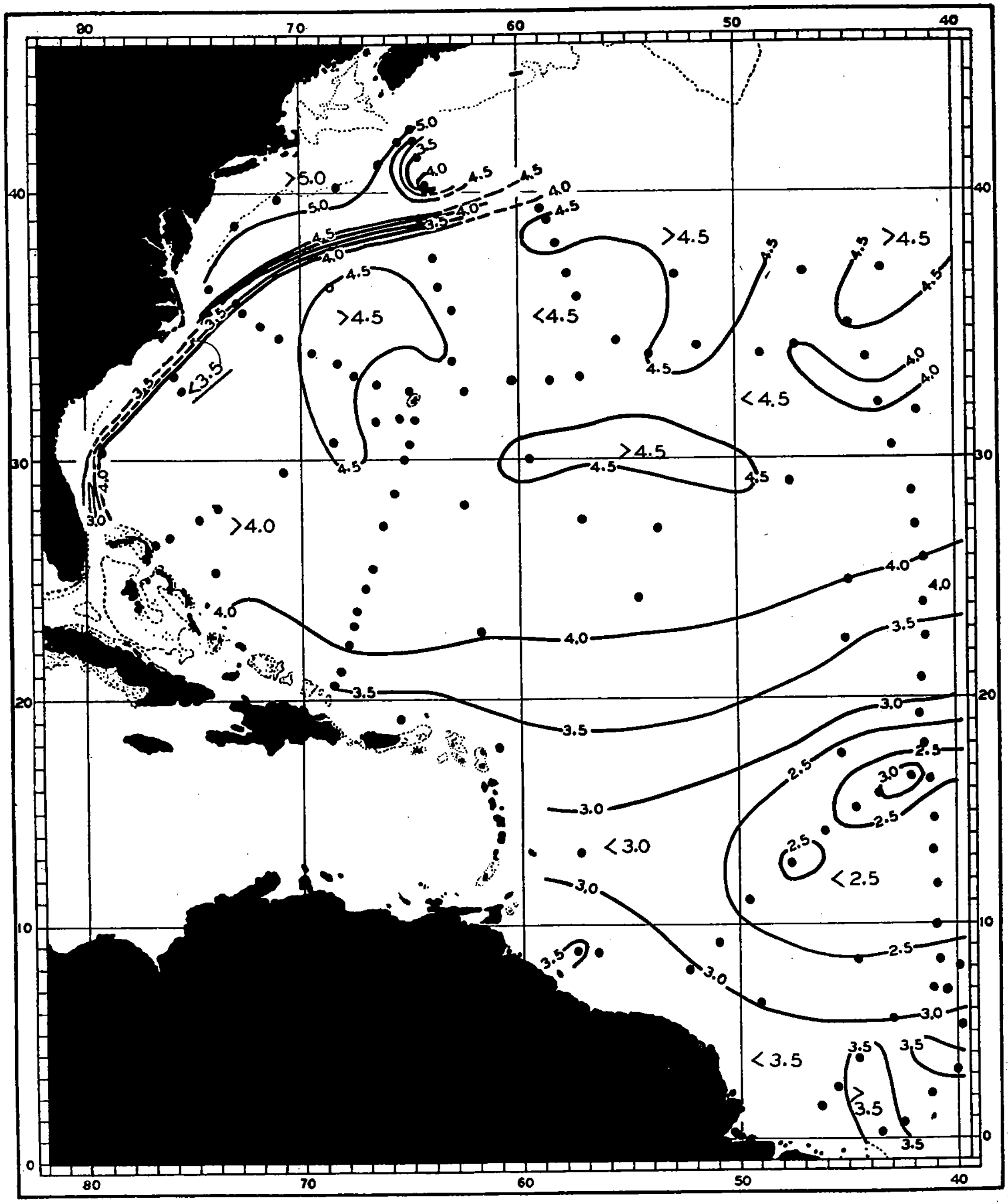

FIG. 29.—Horizontal distribution of oxygen (cc per liter) at 50 meters depth.

the 500 meter plane passed near the minimum oxygen contents of the vertical column which is north of the coldest water.

In deeper water the horizontal gradient becomes less steep, so that at 1000 meters (figs. 31, 32) the gradient along the 40th meridian between 35°N and the equator (4.8 to 3.0 cc per liter, 69 to 42 per cent saturated) stands out in sharp contrast to that in the coastwise convergence. This level intersects the lower part of the oxygen poor layer (fig. 6), and is below the depth of all minimum concentrations in the vertical column; the least oxygen is found between latitudes 18° and 8°N while the coldest water occurs in the most southern part of the section. In still deeper water (below the depths of the oxygen poor layer), at 1500 meters (figs. 33, 34), the oxygen decreased from 5.5 cc per liter in the north to less than 5.0 cc per liter between latitude 24° and 6°N and then increased slightly to the south (>70 to <70 to >70 per cent saturated). Similarly at 2500 meters (figs. 35, 36) oxygen decreases from 6.0 cc in the north to less than 5.5 cc at 16° to 17°N latitude and then increases slightly southward to more than 5.5 cc per liter (80 to <75 to >75 per cent saturated). These results together with general knowledge of the North Atlantic circulation appear to indicate that the horizontal oxygen gradient below 1000 meters depth is correlated with the relative age of the water since aeration. This question is discussed later (see page 82).

Further west (near the longitude of Bermuda) the north south distribution of oxygen through the west central part of the region is illustrated by section F (figs. 17, 18) and section C (figs. 8, 9). Section F, north of latitude 37° 30′N, crosses the three thermal convergences, and off the coast of Nova Scotia horizontal oxygen variations at different depths in the upper 1000 meters are great within short distances and will be discussed in the section on thermal convergences (page 56). From these convergences south to the West Indies, a distance of about 1050 miles, the maximum variation for any horizontal level above 500 meters is only about 1.3 cc per liter and below 1000 meters is 0.6 cc per liter. In sections F and C an approximate parallelism exists between isotherms, isohalines and equal oxygen lines. Thus, south of latitude 40° 30′N (south of the most northerly thermal convergence) the 15° isotherm is almost coincident with the upper 70 per cent isoline, while throughout the whole of both sections between Nova Scotia and the West Indies the 10° isotherm passes close to the center of minimum concentration and the 5° isotherm is approximately parallel and lies close to the lower 70 per cent isoline. It is only in the upper layers of the most northerly thermal convergence that the relationship of isotherms and iso-oxygen lines breaks down, the relative oxygen saturation along the 15° isotherm increasing from 70 to 90 per cent illustrating a reoxygenation of the water having a temperature of 15° and higher near the continental slope (fig. 18).

Along section C, between Bermuda and the West Indies, the horizontal variation of oxygen below 250 meters depth is less than that along section B between the same limits of latitude (figs. 5, 6, 8, 9). Thus, in section C at various depths below 250 meters the horizontal variation is from 0.8 to 0.2 cc per liter, 21 to 3 per cent of saturation, that of section B between the same parallels of latitude is from 1.5 to 0.4 cc per liter, 29 to 4 per cent saturation or about 50 per cent greater.

East West Distribution

From 1000 miles eastward of Bermuda to about 450 miles west of that point, to the vicinity of longitude 72°W, the maximum variation in oxygen at any horizontal level is

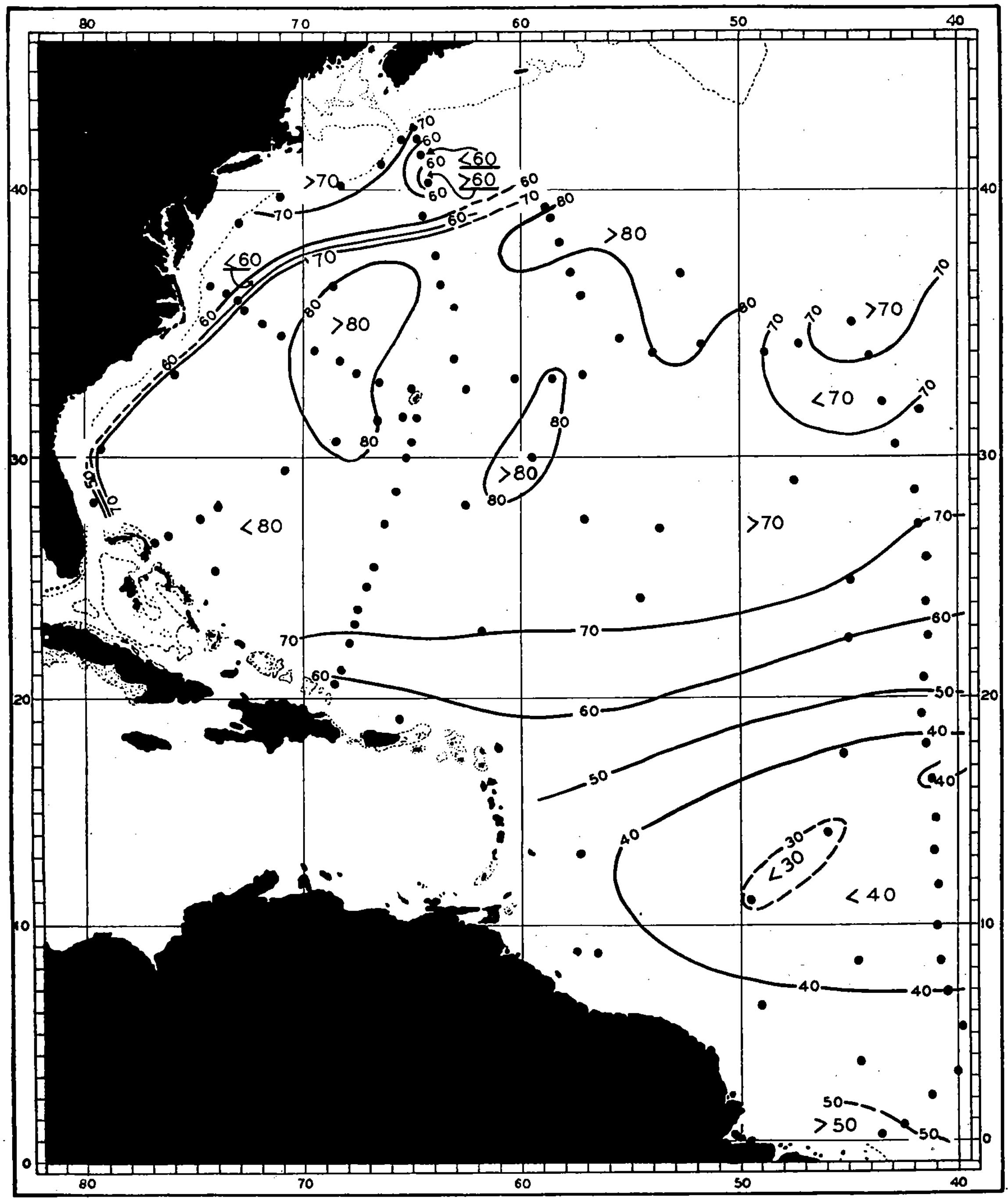

FIG. 30.—Horizontal distribution of oxygen (per cent of total saturation) at 500 meters depth.

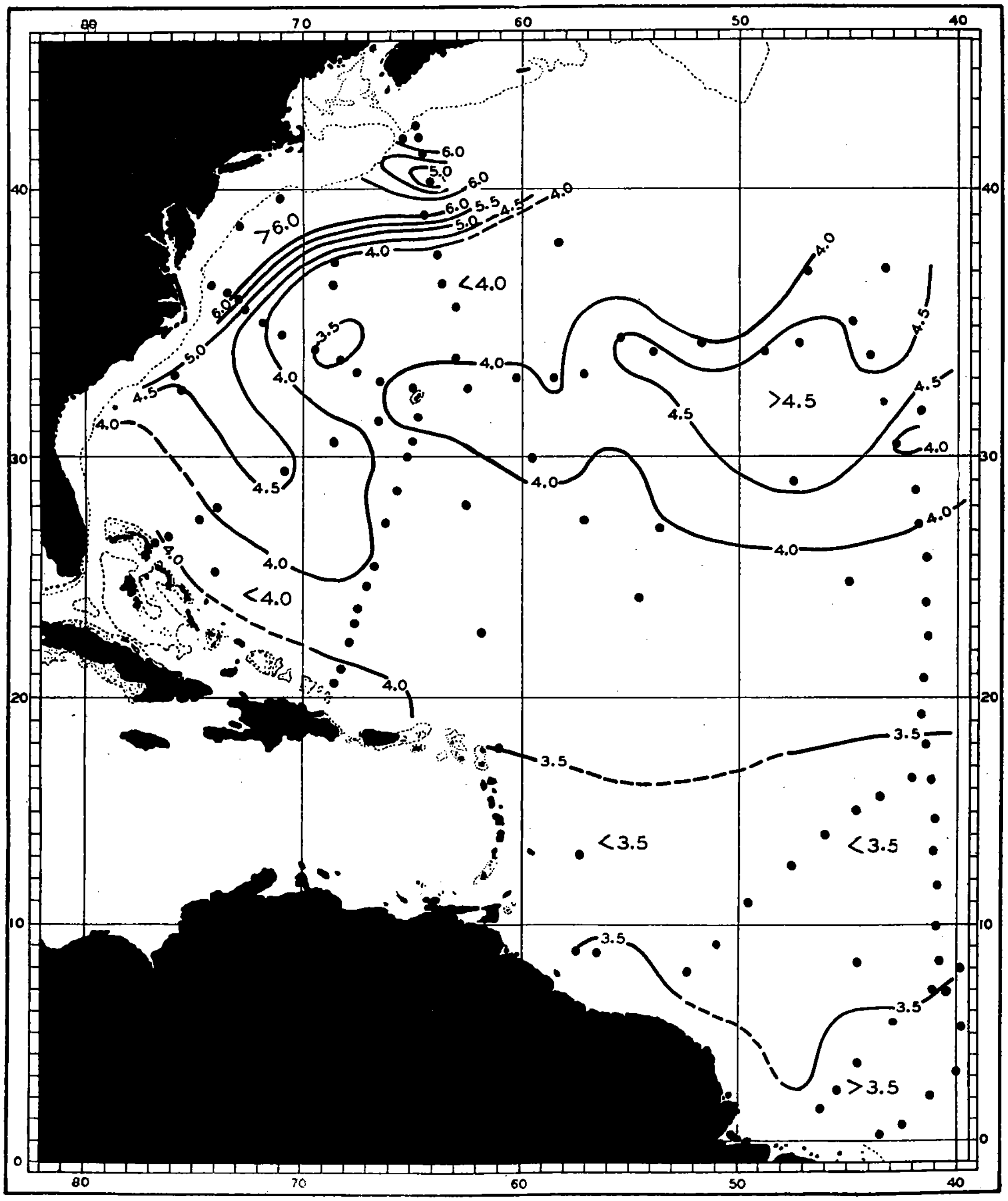

FIG. 31.—Horizontal distribution of oxygen (cc per liter) at 1000 meters depth.

not more than 1.4 cc per liter and usually less than 0.5 cc per liter (figs. 2, 3, 14, 15). Figures 3 and 15 show that east of longitude 72°W the upper 70 per cent isoline is nearly coincident with the 15° isotherm, the lower 70 per cent isoline is nearly coincident with the 5° isotherm, and the 10° isotherm passes near the center of minimum oxygen concentration.

West of longitude 73°W, section E (figs. 14, 15) intersects the principle coastwise thermal convergence and horizontal variations as great as 1.1 cc per liter occur within distances as short as 25 miles. These horizontal oxygen variations in the coastwise thermal convergences are the greatest in the region of investigation, and are discussed in a separate section (page 62). Within the convergence along section E the 5° isotherm continues parallel to the lower 70 per cent isoline, and the 10° isotherm passes near the center of the oxygen poor stratum but the 15° isotherm cuts across the oxygen lines.

Thus, disregarding variations of oxygen content which occur in the thermal convergences, figures 25 to 36 illustrate that in depths less than 1000 meters the small oxygen variations in east west direction (usually 0.5 cc per liter, 10 per cent saturation) are irregular. However, at the 1000 meter level (figs. 31, 32), in the north central part of the area, the oxygen decreased from almost 5.0 cc per liter in the east to about 3.5 cc per liter in the west (69 to 54 per cent of total saturation). But in still deeper water the direction of the east west gradient reverses, there being an increase at 1500 meters (figs. 33, 34) from less than 5.5 cc per liter in the east to about 6.0 cc per liter in the west (<80 to >80 per cent saturation). Similarly at 2500 meters (figs. 35, 36) depth the oxygen increased from less than 5.75 cc per liter in the east to more than 6.25 cc per liter on the western side (<80 to >80 per cent saturation). Thus, in the deepest strata the oxygen content is definitely higher in the western half of the region than that in the eastern.[11]

This east west increase of oxygen in the western basin in depths below 1500 meters is in agreement with Wattenberg's (1929) observations that the deep water of the western part of the Atlantic contains more oxygen than that of the eastern part. The higher oxygen content of the western basin is difficult to explain, but probably is correlated in some way with the age of the water since aeration. It is credited, by Wattenberg, to better conditions in the western basin for the development of deep currents rich in oxygen and to its lesser plankton population. But, as Bigelow and Leslie (1930) point out, in estimating the regional effects of respiration and organic decomposition, the larger animals, above the size of copepods, are probably more important than the small species of plants and animals that were included in Hentschel's (1928) estimates and that form the basis for Wattenberg's conclusions. The phenomena, for the present, must remain unexplained (see page 68).

The Convergences off the American Coast

The most noticeable hydrologic phenomenon appearing in horizontal projections in the region of investigation is the abrupt transition zone of oxygen, temperature, and salinity between high and low values, which roughly follows the trend of the American continent (figs. 25 to 36). Phenomena of this sort (in the case of temperature transition) are now commonly named convergences and this same term can be used equally well for transition belts for other qualities of the water.

[11] The east west increase in oxygen in the water below 1500 meters is made clear by comparing sections D and C with section B and section E with section A.

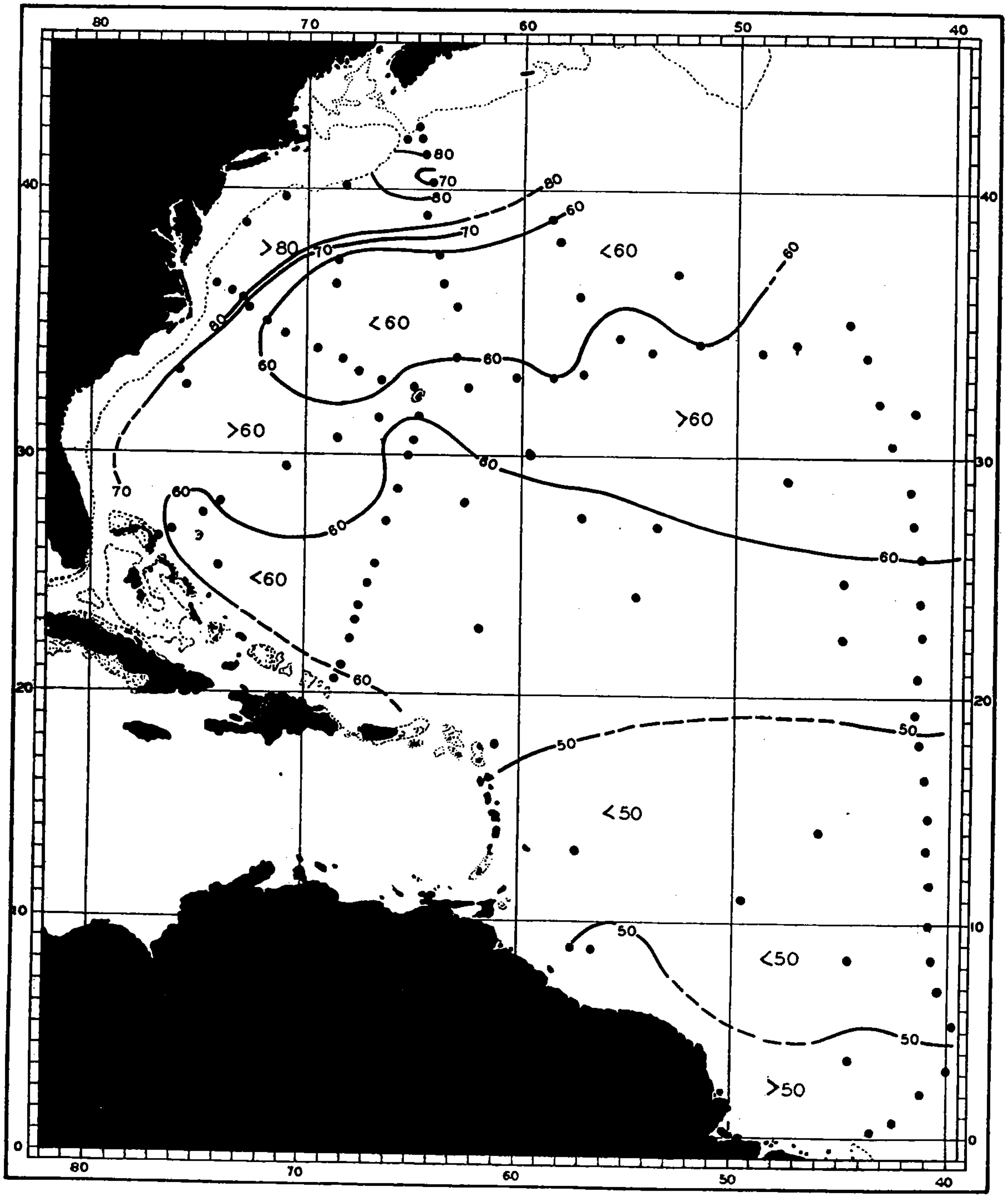

FIG. 32.—Horizontal distribution of oxygen (per cent of total saturation) at 1000 meters depth.

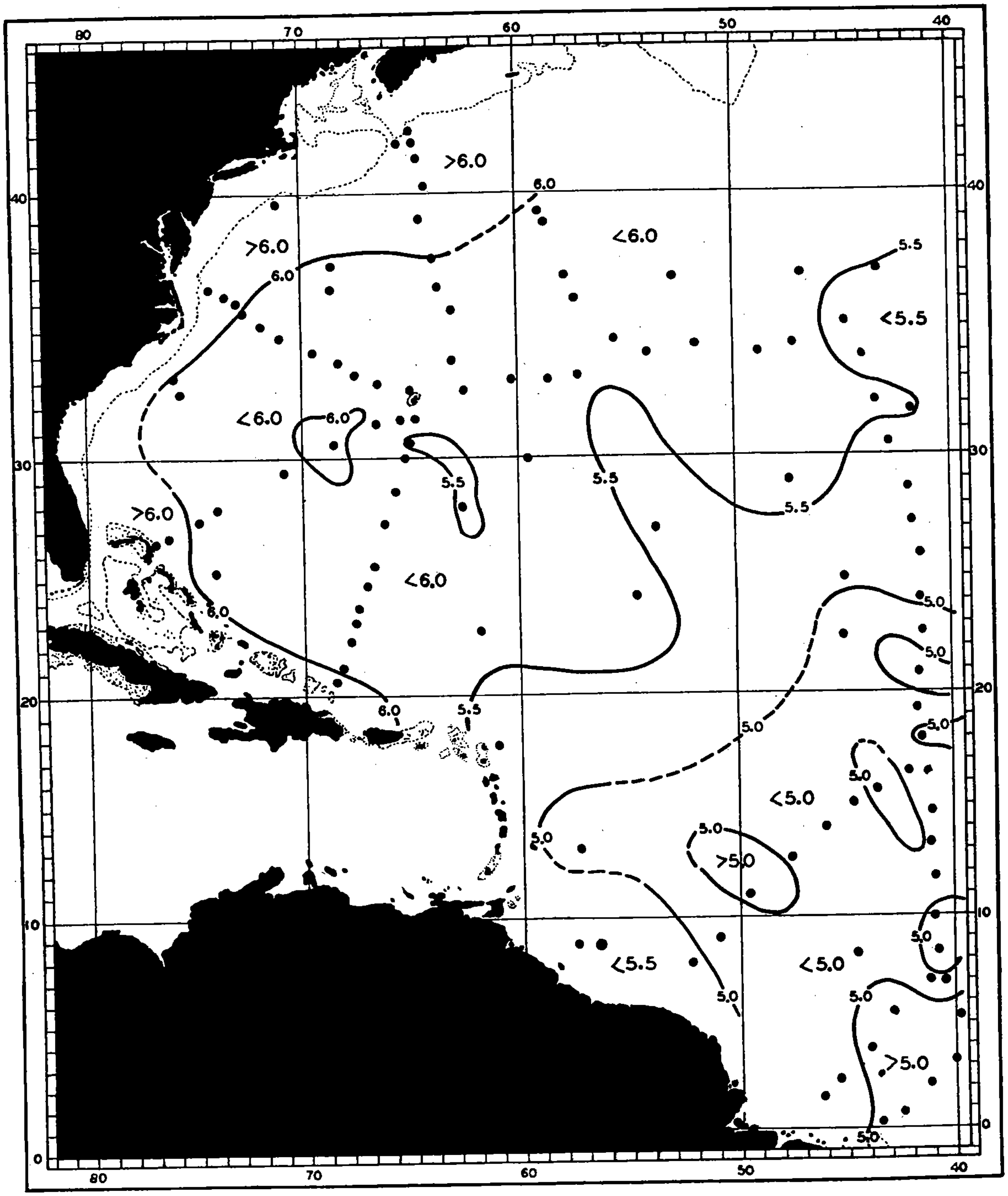

FIG. 33.—Horizontal distribution of oxygen (cc per liter) at 1500 meters depth.

The horizontal distribution of oxygen in the regions of the thermal convergences off the American coast shows a more abrupt transition between high and low values than is known for any other part of the oceans. As the horizontal and vertical variations of oxygen in general may be correlated with similar variations of temperature (page 37) a brief review of the characteristics of the temperature convergences may help to make the situation clear.

The most easterly and most continuous of these convergences extends from the vicinity of the Bahamas, where it is close to the continental shelf, to the offing of Nova Scotia where it lies about 300 miles offshore. In width it appears to vary from about 30 to 60 miles, the maximum occurring off Nova Scotia (compare figs. 14, 15 with 17, 18). It is characterized by the fact that within it all isolines of temperature, salinity and oxygen slope upward sharply from east to west. West of this convergence all isolines lie at a higher level than to the east, and are approximately parallel and horizontal. Only off Chesapeake Bay an exception occurs where in the upper 250 meters there is a small oxygen convergence characterized by a downward sloping of iso-oxygen lines (both absolute and relative) in an east west direction, with no corresponding thermal convergence. In this part of section E the isolines of oxygen (6.0–3.5 cc per liter and 100 to 60 per cent saturated) cut across the horizontal isotherms, and the phenomenon may be the result of an influx of coastal water into the upper part of the section.

The second and third thermal convergences lie between the first convergence[12] and the coast of Nova Scotia; along section F they occur respectively about 200 miles offshore and just off the continental shelf (the two convergences may be continuous so as to form a large cyclonic eddy). The second or intermediate convergence, about 45 miles wide, is characterized by a sharp downward slope of all isolines toward the north, and the third or most northerly convergence is about 60 miles wide and characterized by a sharp upward slope of all isolines toward the coast similar to the first convergence (figs. 17, 18). Thus, as the American coast is approached from the open Atlantic, between depths of 100 and 1500 meters, the first thermal convergence is characterized by the development of a cold wall, and off Nova Scotia the second and third convergences by warm and cold walls respectively.

In all three convergences the horizontal variation of oxygen differs from that of temperature in that it does not proceed in one direction only, a difference resulting from the fact that the minimum oxygen concentrations occur in the midstratum and as the oxygen poor stratum rises within the convergence it lies at a higher level west than east of the latter (figs. 14, 15, 17, 18). Thus, sections E and F, which cross the convergences show that the direction of offshore onshore variation in oxygen as appearing in horizontal projections will depend on the depth of the projection in relation to the vertical distributions of oxygen.

If the horizontal projection across the convergences be made above the depth of the minimum oxygen concentration where it lies nearest to the surface, the oxygen of the first or most easterly thermal convergence will decrease toward the coast; that of the second convergence will increase and that of the third again decrease. Going deeper we observe from the sections that if the horizontal projection be made between the depths of the oxygen minima occurring on either side of the convergence then (provided the

[12] For convenience in discussion the most easterly thermal convergence extending from the Bahamas to the offing of Nova Scotia is called the first or principle convergence, and the two smaller thermal convergences existing between the first convergence and Nova Scotia in north south direction are termed second and third convergences.

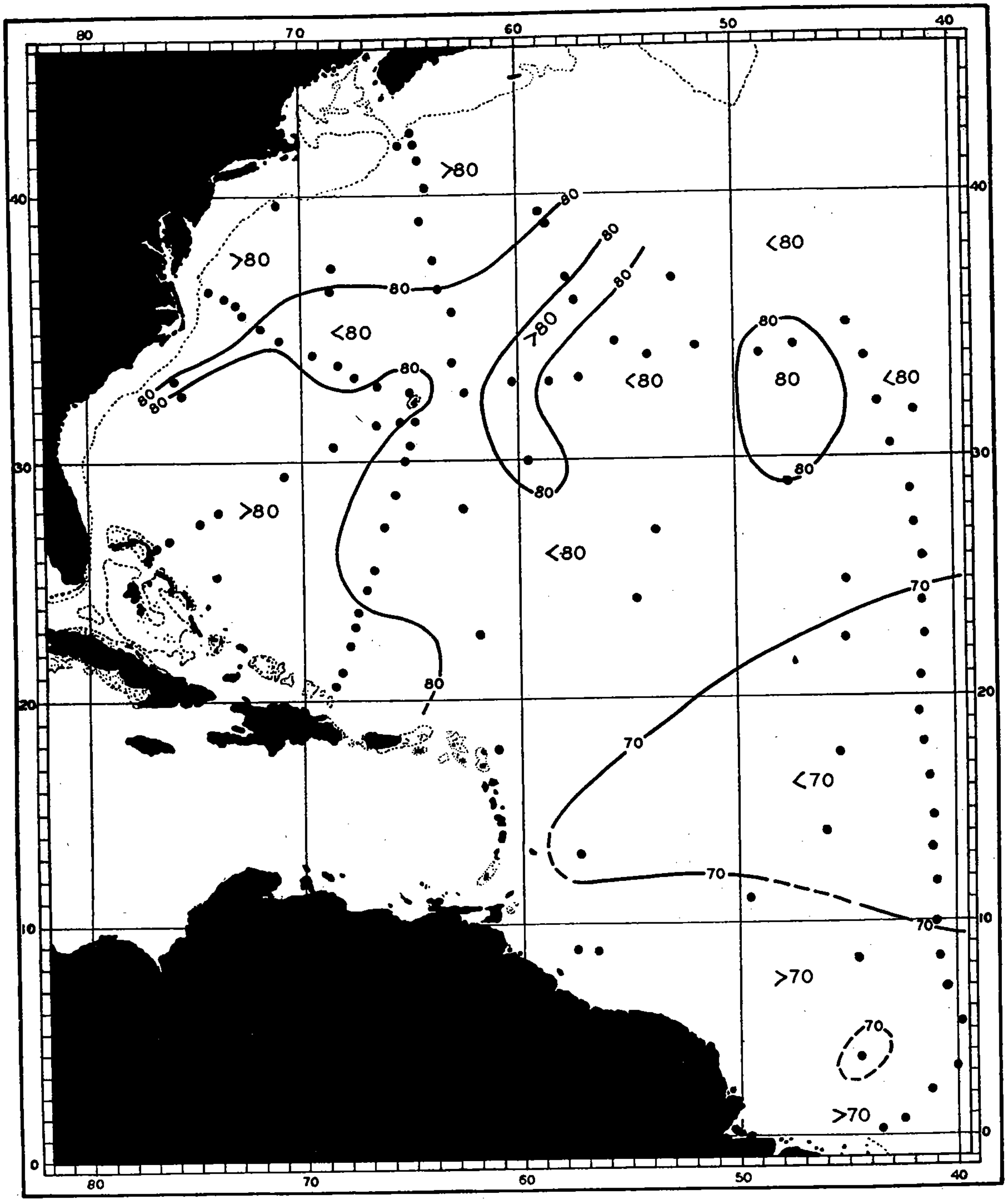

FIG. 34.—Horizontal distribution of oxygen (per cent of total saturation) at 1500 meters depth.

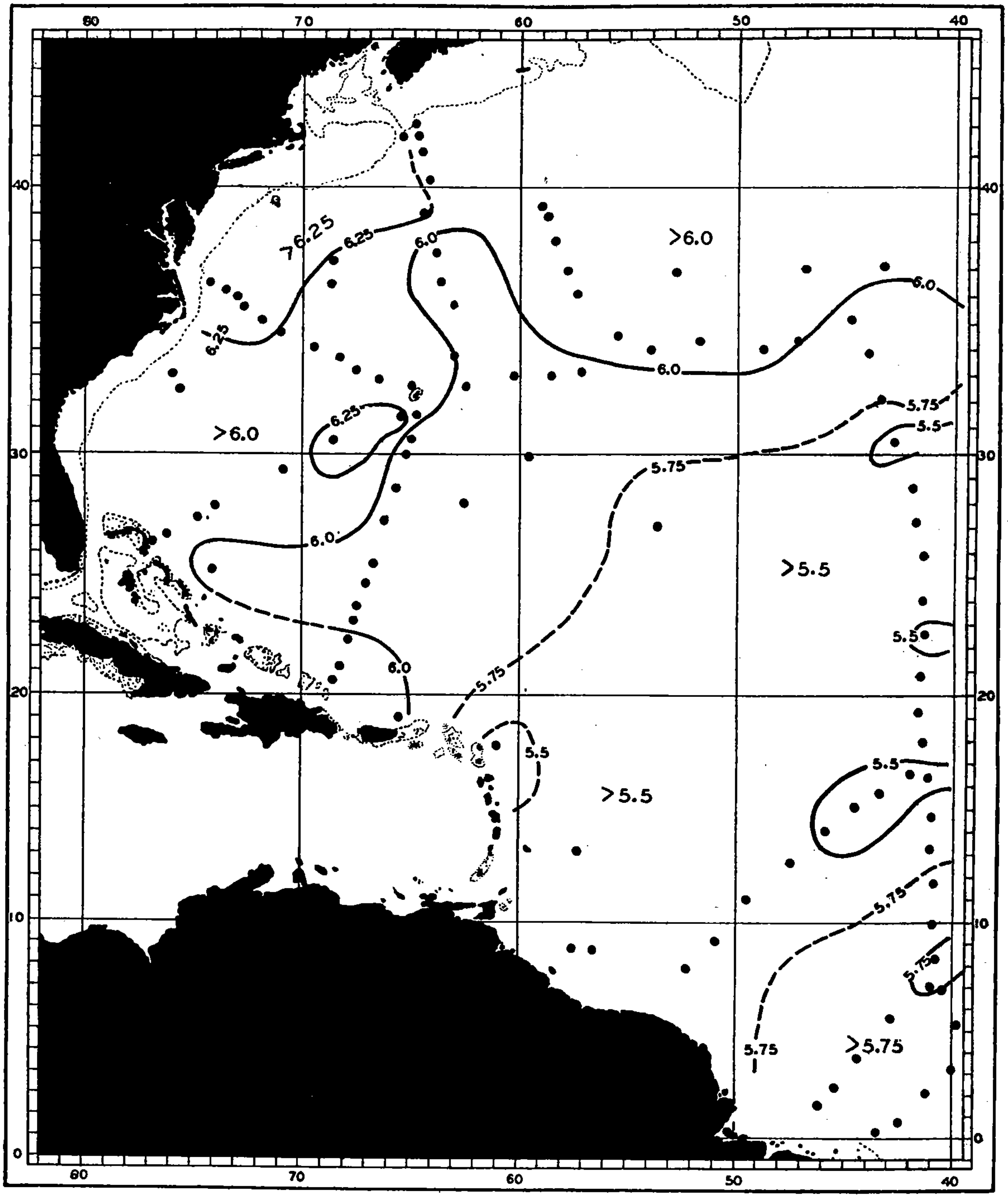

FIG. 35.—Horizontal distribution of oxygen (cc per liter) at 2500 meters depth.

oxygen poor layer is continuous across the convergence) the horizontal variation in oxygen in all three convergences will first decrease and then increase toward the coast. Below the greatest depths at which oxygen concentration is at a minimum the values for oxygen (in horizontal projection) increase toward the coast in the first convergence, decrease in the second convergence and increase again in the third. Hence, not only the direction of horizontal variation in oxygen within the three convergences but also the amount of variation and value of oxygen concentrations as seen in horizontal projection are dependent to a great extent upon the position of the oxygen poor layer in the water column.

The 100 meter level (figs. 25, 26) is above the depth of the oxygen poor layer (figs. 14, 15, 17, 18) in all convergences, consequently oxygen decreased in a coastwise direction along the whole length of the first convergence; the rate of change being from 4.0 cc to less than 3.5 cc in a distance of about 35 miles off the north coast of Florida (latitude 30°N); from 5.0 cc to less than 4.0 cc per liter (90 to <70 per cent saturation) in 50 miles off Chesapeake Bay (latitude 36°N); and from 4.5 cc to less than 4.0 cc per liter (80 to <70 per cent saturated) in 40 miles distance off Nova Scotia (latitude 39°N). Thus, the horizontal gradients range from 0.013 to 0.02 cc per liter per mile. In the oxygen convergence just west of the thermal convergence off Chesapeake Bay (figs. 14, 15) the oxygen increased from less than 4.0 cc per liter to 5.0 cc per liter (<70 to 90 per cent saturation). Descending to 250 meters (figs. 27, 28), the projection passes through the oxygen poor stratum in the chief thermal convergence, but lies just above the depth of its minimum concentration. Consequently, (as at 100 meters) there is an offshore onshore decrease of oxygen, the variation being 1.5 cc per liter (30 per cent of saturation) in an average distance of about sixty miles.

The 500 meter level (figs. 29, 30) intersects the oxygen poor layer of the principle thermal convergence and is between the depths of the oxygen minimum on either side. Thus, the oxygen, in east west direction within this convergence, first decreases, and then increases. Off the north coast of Florida the range is 4.0 to 3.0 to 3.5 cc per liter in a distance of about 30 miles; off Chesapeake Bay the range 4.0 to 3.5 to 4.5 cc per liter (70 to <60 to >60 per cent saturation) in a horizontal distance of approximately 45 miles; off Nova Scotia the range is about the same as off Chesapeake Bay. The horizontal oxygen gradient at this depth works out at 0.03 to 0.05 cc per liter per mile.

In deeper water the horizontal gradient changes in character depending upon the vertical distribution of oxygen within the convergence as previously discussed. Descending to 1000 meters (figs. 31, 32) the horizontal projection is just below the depth of the minimum oxygen content in the water on the east side of the first thermal convergence (figs. 14, 15, 17, 18) so that this level shows successively larger quantities of dissolved oxygen in westerly direction across the convergence corresponding to the decrease in temperature. Thus, from offshore the oxygen increased toward the coast from 4.0 to 6.0 cc per liter (60 to 80 per cent saturation) in the horizontal distances of 85 and 70 miles, respectively, in the offings of Chesapeake Bay and Nova Scotia, or an average horizontal oxygen gradient of approximately 0.026 cc per liter per mile. At still greater depths the first convergence loosens, and at a depth of 1500 meters (figs. 33, 34) its eastern limit is marked by the position of the isoline of 6.0 cc per liter.

The second and third thermal convergences, lying between the first thermal convergence and the coast of Nova Scotia, also show sharply developed horizontal gradients of oxygen. Thus, at 100 meters depth (figs. 25, 26) the oxygen variation in the second convergence proceeds in one direction only but in opposite direction to that of the

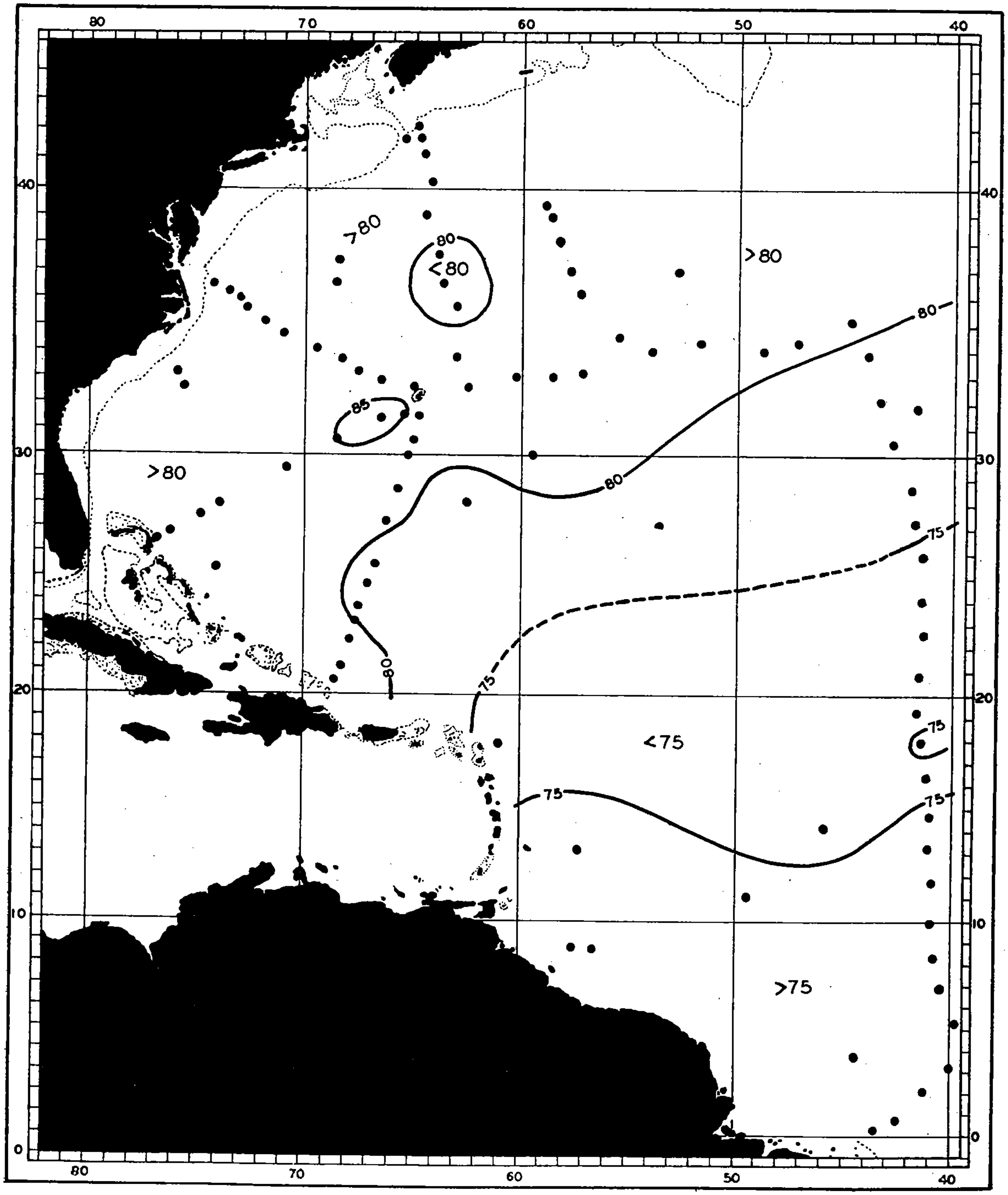

FIG. 36.—Horizontal distribution of oxygen (per cent of total saturation) at 2500 meters depth.

first, increasing from 4.0 to 4.5 cc per liter (70 to 80 per cent saturation) in a distance of about 20 miles in south to north direction. The third thermal convergence does not extend sufficiently close to the surface to show a horizontal gradient of oxygen at this depth.

The 250 meter plane intersects the oxygen poor stratum both in the second and the third convergence but lies above the depth of minimum concentration so in south north direction the oxygen increases from 3.5 cc per liter to 4.5 cc per liter (60 to 80 per cent saturation) in the second convergence, and decreases from 4.5 to 3.5 cc per liter (80 to 60 per cent saturation) in the third (figs. 27, 28). Thus, an oxygen maximum occurs between the second and third convergences, and the amplitude of the horizontal gradient is approximately equal to that for the first convergence. The 500 meter level intersects the undulating oxygen poor midstratum off Nova Scotia and lies between the depths of the oxygen minima in the second and third convergences (figs. 18, 29, 30). Thus, in the second convergence, from south to north, the oxygen ranges from 4.5 cc to 3.5 cc per liter then to 4.0 cc per liter (60 to <60 to >60 per cent saturation) in a distance of 25 miles, and in the third convergence, in the same direction, the oxygen ranges from 4.0 to 3.5 cc then to 4.5 cc per liter (>60 to <60 to 70 per cent saturation) in a distance of 80 miles.

Between 500 and 1000 meters the character of the horizontal gradient changes as the horizontal projections pass below the depth of the vertical oxygen minima. As illustrated by the 1000 meter chart (figs. 31, 32) oxygen in the second convergence decreases south to north from 6.0 cc per liter to 4.5 cc per liter (80 to <70 per cent saturation) then in the third thermal convergence increases from 4.5 cc to 6.0 cc per liter (<70 to >80 per cent saturated). In the underlying water, as the vertical variation of oxygen becomes less and the convergence loosens the horizontal gradient is less marked, being barely perceptible at 1500 meters depth (figs. 33, 34).

COMPARISON OF OXYGEN CONTENT OF THE WESTERN NORTH ATLANTIC BASIN WITH THAT OF OTHER OCEANIC AREAS

Comparison With Other Parts of the North Atlantic

Oxygen content is usually greater in the high latitudes of the North Atlantic but the vertical distribution is not essentially different than that described here for the western basin. From the observations of the Danish Ingolf expedition (Knudsen, 1899) in the seas around Iceland, oxygen decreases from the highly saturated surface layer to a minimum at about 1000 meters depth. In this region the lowest minimum recorded was 61 per cent of total saturation while usually it was above 80 per cent.

In the shallow waters of the north Siberian shelf Sverdrup (1929) has shown that a regular seasonal variation of oxygen occurs in the surface layers which is attributed to the growth of the phytoplankton. The oxygen may range from about 88 per cent of total saturation in the winter months to as much as 112 per cent in summer. The greatest content occurs in the pack ice where the oxygen produced by photosynthesis has difficulty in escaping to the air and thus accumulates. The degree of summer supersaturation of the Arctic region frequently exceeds anything encountered for the western North Atlantic basin, and (considering the difference in summer temperatures between the two regions, 20° or more) there is an enormous accumulation of oxygen in the waters of high latitudes.

Sverdrup (1929) has pointed out that in high latitudes the depth below the surface to which supersaturation extends suggests certain conditions characterizing the region in which the water originated. For instance, where this extends to 50 meters or so it may be assumed that the water originated in a region free of ice; whereas when the supersaturated layer is very thin the water originated from an area with floating ice, where, because of light conditions, the phytoplankton was confined to a very shallow surface layer.

In the Arctic waters north of Spitzbergen the oxygen maximum was found at a depth of 10–25 meters, the greatest supersaturation recorded was 111 per cent, with an average at 25 meters depth of 105 per cent. The average oxygen content at 100 meters was 89 per cent (Sverdrup, 1933).

On the other hand, even lower oxygen concentrations may occur sometimes in the subsurface layers of high latitudes than those encountered in the western North Atlantic basin. In a very thin heavy layer of bottom water on the east Siberian shelf Sverdrup noted a concentration of only 18 per cent whereas values as low as 21 per cent occur in the transition zone between light upper and heavy bottom layers. These low concentrations are undoubtedly the result of an intensive oxidation of the large quantities of organic substances produced during the short growing season.

The "Margrethe" investigations (Jacobsen, 1916) carry the north south comparison from the Faeroes to the West Indies showing a decrease from north east to south west at about 1000 meters depth. Jacobsen explains this decrease on the basis that somewhere in the northern part of the Atlantic water is cut off from contact with the atmosphere after which it moves toward the south west, gradually becoming deficient in oxygen as the latter is used by organisms. He further suggests that the oxygen content of the midstratum is lower than that of the deeper water because the supply to it takes place more slowly. That this latter explanation may not be correct is discussed below (page 82).

Jacobsen's account of the general oxygen content of the midstratum of the Atlantic was corroborated by Brennecke's (1921) north south oxygen profile, which shows a definite decrease in the minimum concentration from 80–70 per cent at 60°N latitude (1000 meters depth) to less than 30 per cent of total saturation at 10°N latitude (600–800 meters depth). This distribution of oxygen is in general agreement with the "Atlantis" north south profile along the 40th meridian (section B; figs. 5, 6) where the minimum concentration was found to decrease from 61 per cent (4.0 cc per liter) at 35°N latitude at 1000 meters depth to 27 per cent of saturation (1.7 cc per liter) at 15°N latitude at 400 meters depth (page 14). However, the minimum oxygen concentration in the "Atlantis" section B occurs five degrees further north and 200–400 meters closer to the surface than it does in the "Deutschland" profile (lying 4 degrees west of section B). Thus, comparing available oxygen values along the 15° parallel at 400 meters depth we find that, according to the "Deutschland" profile, the value is between 2.0 and 2.5 cc per liter or 30 to 40 per cent of total saturation; also at "Meteor" station 286 (15° 4′N, 44° 39′W; Wattenberg, 1933) the value at 400 meters is given as 2.02 cc per liter, but at this station the oxygen content is still decreasing vertically at 400 meters, and at 500 meters a value of 1.80 cc per liter was recorded which is nearly equal to the "Atlantis" minimum (about 225 miles further east).

There is also a similar discrepancy between older and more recent observations[13] with regard to oxygen values at the locality ("Deutschland" sta. 21, 9° 35′N, 43° 54′W) where the "Deutschland" found the minimum for the North Atlantic. Here "Deutschland"

[13] Oxygen observations in North Atlantic were made: "Deutschland" 1911; "Dana" 1921; "Meteor" 1927; "Atlantis" 1933.

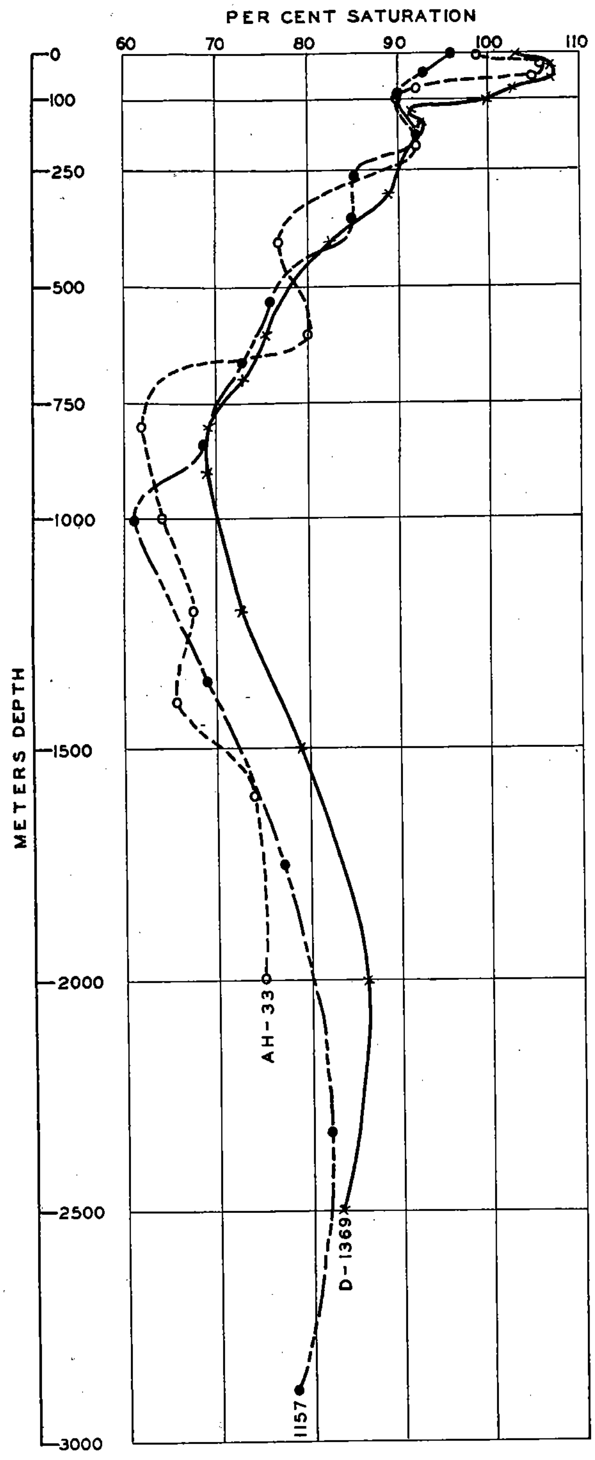

FIG. 37. Vertical distribution of oxygen (per cent of total saturation) at "Armauer-Hansen" station 33 (AH-33, 35° 35′N, 14° 10′W; Gaarder, 1925); "Dana" station 1369 (D-1369, 35° 44′N, 29° 33′W; Schmidt, 1929); "Atlantis" station 1157 (35° 10′N, 44° 40′W).

recorded 1.85 cc per liter, 27 per cent of total saturation, at 770 meters but at a neighboring locality, about 3° east, "Atlantis" profile shows 2.9 cc per liter, 41 per cent saturated, and two "Meteor" stations to the west (Wattenberg, 1933; sta. 289, 11° 2′N, 49° 33′W; sta. 290, 9° 07′N, 50° 57′W) found 2.83 cc and 3.00 cc per liter respectively for 800 meters depth; also just to the south of "Deutschland" station 21 "Dana" (sta. 1171, 8° 19′N, 44° 35′W; Schmidt, 1929) records 2.82 cc per liter, 40 per cent of total saturation for 800 meters depth.

As the "Deutschland" observations were made with highest obtainable accuracy we may conclude tentatively from these discrepancies that the geographic location of the minimum oxygen concentration in the western North Atlantic changed in the interim between 1911 and the date of more recent observations, namely 1927 to 1933. On the other hand, the horizontal oxygen distribution (page 44) is such that the apparent position and depth of minimum oxygen concentration in the western North Atlantic as derived from a two-dimensional section may vary according to the precise locations where the observations are taken. Hence, for a rational picture of the oxygen content of the ocean we must extend our observations to cover three dimensions, and furthermore the observations should be made within as short a period of time as possible.

On the eastern side of the Atlantic there are available for comparison with the western basin the oxygen observations made by "Armauer-Hansen" (Helland-Hansen, 1914), "Planet" (Brennecke, 1909), "Thor," (Jacobsen, 1912), "Deutschland" (Brennecke, 1921), and "Margrethe" (Jacobsen, 1916) all of which were combined with the "Armauer-Hansen" material of 1913–1914 and discussed by Gaarder (1925).

In the region between the Azores and Rockall Bank (Gaarder's section 5) the vertical distribution differs but slightly from that in the northeastern part of the western basin, oxygen at the surface being 5.3–6.2 cc per liter (i.e., supersaturated), decreasing to a minimum of 4.3–4.7 cc per liter (66–72 per cent saturated) in the vicinity of 1000 meters, and rising again to >5.5 cc per liter (about 80 per cent saturated) below 1500 meters. Thus, in the water just north of the Azores the minimum oxygen values are somewhat higher than at about the same latitude in the northeastern part of the western basin, but there is little difference in the oxygen content of the deep water below 1500 meters (compare with section A, figs. 2, 3; section F, figs. 17, 18; and 1500 meter charts, figs. 33, 34).

Previous evidence that the oxygen content of the midstratum was higher in the eastern than in the western side of the North Atlantic at mid latitudes was brought out by Bigelow and Leslie (1930) who showed that the mean value at depths of 800–900 meters on the western side (out to longitude 55°W) between latitudes 20° to 35°N was about 3.5 cc per liter (based on nineteen "Dana" stations) as compared to 4.0–4.5 cc per liter for approximately the same depth between Spain, Morocco and the Azores (recorded by "Armauer-Hansen," Gaarder, 1925).

Along latitude 35°N, the oxygen content of the eastern half of the Atlantic represented by three stations (fig. 37; "Armauer-Hansen" sta. 33, 35° 35'N, 14° 10'W; "Dana" sta. 1369, 35° 44'N, 29° 33'W; "Atlantis" sta. 1157, 35° 10'N, 44° 40'W) shows that differences for any depth vary less than 10 per cent of total saturation,[14] and comparing with the horizontal oxygen distribution of sections A and E in the western basin (page 53, figs. 2, 3, 14, 15), it is seen that across the whole of the North Atlantic in the vicinity of latitude 35°, west of the American coastwise thermal convergence, the horizontal oxygen variation at any depth between highest and lowest values generally is not over 10 per cent of total saturation. The minimum oxygen concentrations in the eastern Atlantic at this latitude are more than 60 per cent saturated, thus, as previously pointed out, the oxygen content of the midstratum is lowest in the western basin. Among the three stations (fig. 37) the greatest divergence in oxygen content occurs below 1000 meters depth where at the extreme eastern side of the Atlantic (represented by "Armauer-Hansen" sta. 33, fig. 37) oxygen values were more similar to those characterizing the central Atlantic (represented by "Atlantis" sta. 1157) than they were to those of the east central part (represented by "Dana" sta. 1369), but below 1600 meters "Armauer-Hansen" station 33 showed values as much as 5 per cent lower than "Atlantis" station 1157. The east central Atlantic just south of the Azores (represented by "Dana" sta. 1369) had a higher oxygen content below 1000 meters than either the extreme eastern side or the central part; being similar to the water below 1000 meters just east of the American coastwise convergence in the western basin (figs. 14, 15). Thus, in the water at 2000 meters depth, near the 35th parallel, the oxygen content from east to west undulates, being 75 per cent saturated for longitude 14°W; 86 per cent for longitude 29° 30'W; 80 per cent for longitude 44° 40'W; and 86 per cent for longitude 72°W.

Further south in the North Atlantic, between latitudes 20° and 25°N, a comparison of the oxygen content of eastern and western parts is based on a section constructed on "Dana" (Schmidt, 1929), "Deutschland" (Brennecke, 1921), and "Atlantis" observations (fig. 38). In the water below 1200 meters there is a definite increase in oxygen from

[14] Applies to depths greater than 100 meters; in the surface layers wide local variations of saturation may occur on account of photosynthesis (see page 44).

east to west. On the extreme eastern side, near the African coast, the oxygen content of the water below 800 meters is very poor (40 to 60 per cent saturated) which Jacobsen (1929) attributes to the Mediterranean water which has a low oxygen content before it

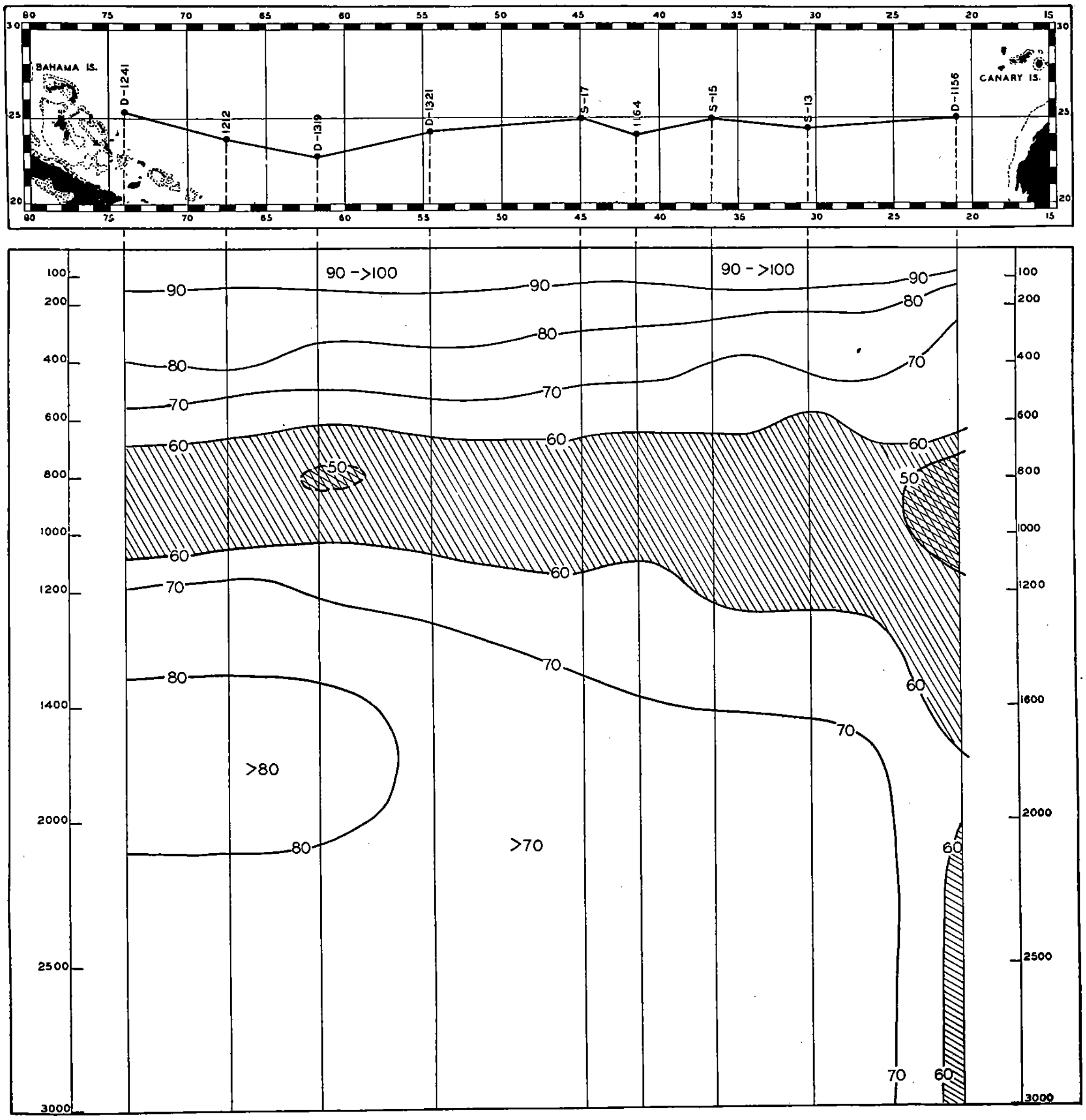

FIG. 38.—East west vertical distribution of oxygen (per cent of total saturation) across North Atlantic at 20°–25°N latitude. Section based on "Dana" (D) stations (Schmidt, 1929), "Deutschland" (S) stations (Brennecke, 1921) and "Atlantis" (unlettered) stations.

enters the area, and to the slow renewal of water in the deepest strata. Below 1200 meters the east west distribution of oxygen corroborates Wattenberg's (1929) conclusion that the deep water contains more oxygen in the western Atlantic than in the eastern. Above

1000 meters depth, except at the extreme eastern side, the oxygen content is relatively uniform, from east to west the maximum difference between highest and lowest saturation value at any level is not over 10 per cent of relative saturation. The oxygen poor layer shows an approximately uniform content (except near the African coast) across the whole stretch in which respect it differs from the midstrata further north. However, still further south, in the equatorial North Atlantic, lower minimum oxygen concentrations occur on the eastern rather than the western side which is a reversal of the case further north at midlatitudes (page 67). Thus, for example, on the eastern side, "Meteor" station 264 (10° 12′N, 26° 36′W; Wattenberg, 1933) records a minimum of 0.61 cc per liter at 400 meters depth whereas in the western basin, at the same latitudes, "Meteor" (sta. 289, 11° 2′N, 49° 33′W) and "Atlantis" (sta. 1173, 9° 57′N, 40° 55′W) minima values for the middepths are 1.95–2.30 cc per liter.

Comparison with the South Atlantic

Three meridional oxygen sections have been published for the South Atlantic ocean: Brennecke's (1921) based on the "Deutschland" observations, lies throughout most of its extent in the western side; Wattenberg's (1929) in the eastern side; and Deacon's (1933) follows the 30th meridian.

The general north south distribution is essentially similar to that for the North Atlantic. Wattenberg's (1929) observations show the minimum concentration for the water column which, less than 4.5 cc per liter at 1000–2000 meters depth, at 50°S latitude, diminishes in value and rises surfaceward toward the north so that at 15°–9°S latitude it is less than 1 cc per liter at 400–500 meters depth. Below 2000 meters the oxygen content is usually greater than 5.0 cc per liter. Further west, along the 30th meridian, the oxygen distribution is essentially the same except that, in tropical latitudes, minima values in the midstratum are higher here than near the African coast.

The east west distribution of oxygen in tropical waters along the 9° parallel (based on "Meteor" data; Wattenberg, 1929) shows that an oxygen minimum, less than 1.0 cc per liter, lying between 200 and 500 meters depth, extends westward from near the African coast to about 2° west longitude and then increases in value toward the west, so that near the South American coast the minimum concentration is more than 4.0 cc per liter. In still greater depths a similar east west gradient characterizes the water; below 2000 meters the oxygen in general increases from about 5.0 cc per liter just off the African coast to more than 5.5 cc per liter on the South American side. This east west gradient (for the oxygen poor layer and deeper water) is similar to conditions existing in the equatorial north Atlantic.

The oxygen content of the Antarctic surface water like that of high latitudes of the North Atlantic (page 64) has a seasonal variation (ranging from less than 90 per cent in winter to more than 100 per cent in summer) which is apparently the result of phytoplanktonic activity.

Comparison with the Pacific

Comparisons of the oxygen contents of the Atlantic and Pacific oceans have been made within recent years by Bigelow and Leslie (1930), Moberg (1930, 1930A), Ito (1930), and Thomsen (1931). The main facts of vertical distribution of oxygen, a highly saturated surface layer of variable thickness from which the oxygen content decreases to a minimum in the midstratum and then increases again in the deeper water, is essentially the same for both oceans. Like the Atlantic there exists east west oxygen gradients, the waters of the western Pacific being better aerated than those of the eastern. Thus, Moberg (1930) on the basis of the "Carnegie" material from the eastern Pacific between the California coast and the Hawaiian Islands shows that the oxygen minimum at a depth of 700 to 800 meters varies from 0.21 to 0.96 cc per liter or 3 to 12 per cent of total saturation, whereas Ito's (1930) data for the southwestern part of the North Pacific (0°–34°N latitude, 127°–163°W longitude) indicates that minimum oxygen values, occurring between 300 and 1500 meters depth vary from 1.02 to 3.92 cc per liter, or 16 to 57 per cent of total saturation. Similarly, in the deep water, Moberg for the eastern Pacific obtains an average value at 2000 meters depth of 2.1 cc per liter between equator and 20°N and 1.7 cc per liter between 20°N and 37°N, whereas in the western side Ito's values for the 1500 meter level range from 1.84 to 3.06 cc per liter (24 to 40 per cent of total saturation) between 0° and 20°N and 2.01 to 4.46 cc per liter (27 to 59 per cent of total saturation) for latitude 20° to 34°N. Also the "Dana" section across the tropical Pacific indicates higher values in the western side both for midstratum and the deeper water (Thomsen, 1931).

The very low oxygen content and the great thickness of the oxygen poor layer which characterizes certain parts of the Pacific is representative of one of the greatest ecologic differences between the two oceans. Thus, in the tropical waters of the eastern Pacific, at "Carnegie" station 151, between depths of 100 and 400 meters, the oxygen content ranged from 0.03 to 0.06 cc per liter or from 0.5 to 1.0 per cent of total saturation and in general on this side of the Pacific minimum values of 0.2 to 0.8 cc per liter were common. Contrasting with this, the minimum value observed by "Atlantis" in the western tropical Atlantic was 1.7 cc per liter (27 per cent saturation) while Wattenberg's (1929, 1933) minima for the midstrata both of north and south Atlantic are just under 1 cc per liter.

In the deeper strata, below 1500 meters, available data similarly show much lower oxygen values in the Pacific than in the Atlantic. Thus, in the eastern Pacific Moberg (1930A) finds average values ranging from 1.7 to 3.4 cc per liter between 13°S and 37°N at 2000–3500 meters depth; and in the western part between 0° and 34°N latitude Ito's (1930) data indicate that the values at 1500 meters range from 1.84 to 4.46 cc per liter. These values contrast with 5.0 cc to more than 6 cc per liter in the western North Atlantic below 1500 meters (figs. 30 to 33); indeed it is safe to say that oxygen values below 2000 meters are as high as 5–6 cc per liter throughout the north and south Atlantic.

Schmidt (1925), Bigelow and Leslie (1930) and Moberg (1930A) have suggested that the difference in oxygen content between the Pacific and the Atlantic ocean is due to a greater staleness of the water in the former rather than to a greater consumption of oxygen per unit. From the small amount of evidence at hand this suggestion seems reasonable and the present discussion adds nothing toward the solution of this particular problem.

PART II

THEORETICAL

CRITERIA FOR THEORETICAL ANALYSIS

Selection of Particular Part of Water Column to be Analyzed

The life history of a water mass after it sinks from the surface of the ocean into the depths is a complex series of events about which little is known (page 5), so that evaluation of its relative oxygen content gives but little information regarding the biochemical activity which is responsible for reductions in oxygen, beyond indicating the approximate amount of oxygen which has been consumed since the water left the surface. The oxygen value for any time and place may be said to represent the balance which exists after a certain amount of consumption or regeneration in situ has occurred, and also after a certain amount of transportation to and from other regions. In general all factors are unknown variables. Nevertheless, if it be possible in any instance to find any particular part of the water column in which there is no production of oxygen by photosynthesis, and within which the history of the disappearance of dissolved oxygen may be traced through several years, important information may be obtained as to the rate of consumption. And this, in turn, may be used as a measure of the intensity of the biochemical activity to which the ultimate reduction of dissolved oxygen in the ocean is directly related. Obviously in such an analysis the effect of physical transporting agencies on oxygen distribution must be separated from the biochemical factors causing consumption. And for this reason the part of the water column selected for analysis must be one which is not only free from photosynthetic activities, but one removed from influence of any physical agencies which would significantly alter the oxygen content without leaving any record. That is to say we must seek a stratum that is not subject to local secular enrichments of oxygen from the air or from photosynthesis, but one in which (for all practical purposes) the supply of oxygen is maintained by horizontal currents. A second requirement is that the stratum to be analyzed have a relatively low oxygen content with respect to the remainder of the water column; this condition indicates that active consumption is occurring at the depths in question. In the western North Atlantic it is apparent that these conditions are met in the oxygen poor layer (page 41); at least approximately so.

Selection of Particular Series of Stations for Analysis

There are certain fundamental conditions upon which the validity of the theoretical discussion depends, and which govern the selection of the particular line of stations to be studied. These are:

1. The oxygen content along the chosen section should show a definitely increasing or decreasing gradient over considerable distance.
2. The physical characters (temperature, salinity, and salinity anomaly) should be such as to indicate the origin of the stratum, and also show that it is fairly homogeneous over considerable distance.
3. The series of stations should be parallel to a principle directional component and

the characteristics of the water should be such that the average velocity of this component can be estimated.

That all these requirements are met in "Atlantis" section B (page 14; figs. 5, 6) is brought out in the following discussion.

PREREQUISITE ASSUMPTIONS AND CALCULATIONS PRELIMINARY TO DETERMINING OXYGEN CONSUMPTION IN THE OXYGEN POOR LAYER OF "ATLANTIS" SECTION B

Average Oxygen Gradient of the Oxygen Poor Layer

The average oxygen content for the oxygen poor layer[3] shows a definite north south gradient; it decreases both from the northern (4.0 cc per liter, 60 per cent saturated) and southern (3.71 cc per liter, 52 per cent saturated) ends of section B to a minimum (2.82 cc per liter, 41.8 per cent saturated) at about 15° north latitude (table 11, fig. 39).

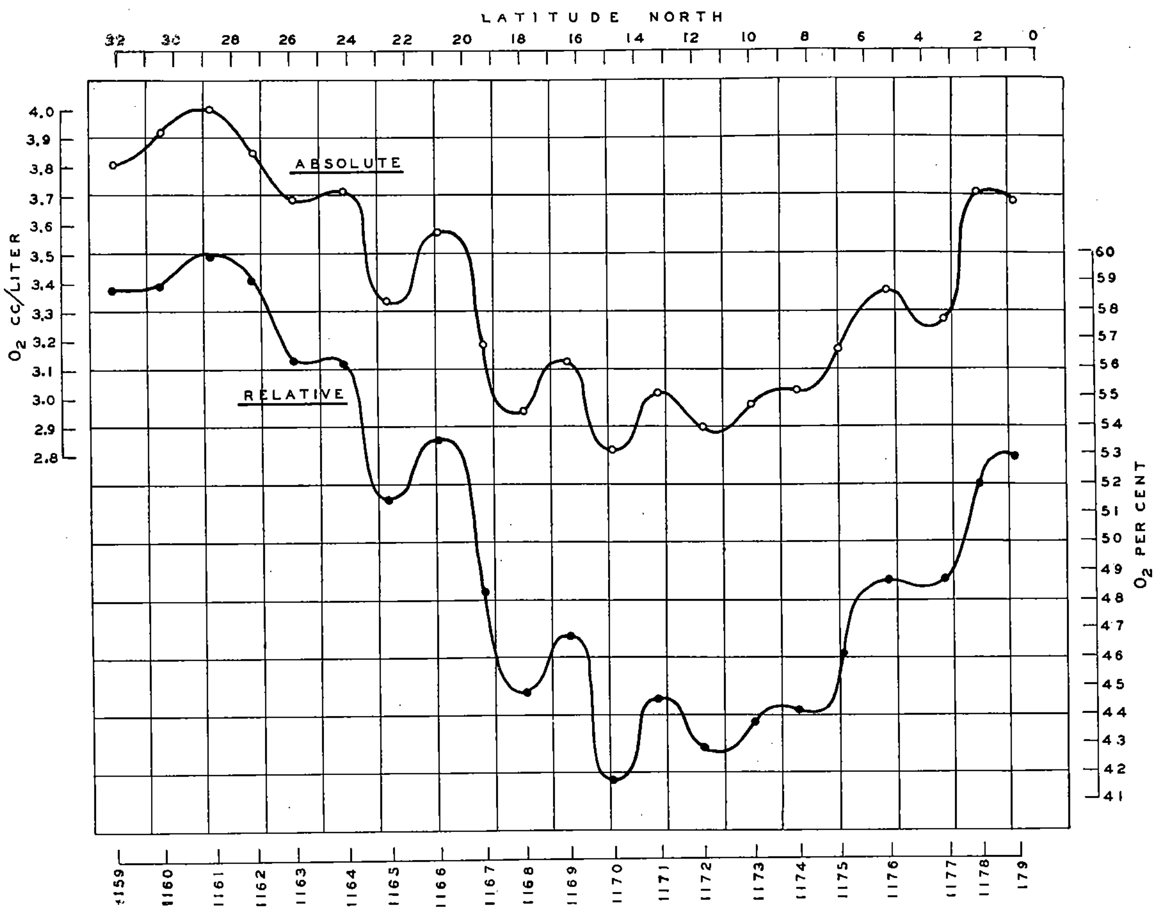

Fig. 39.—Average oxygen content of oxygen poor layer in "Atlantis" section B.

[3]Ibid. Page 11.

Origin and Homogeneity of the Water of the Oxygen Poor Layer

The fact that a north south oxygen gradient of the kind just stated exists in the oxygen poor layer along section B might result from water entering into the opposite (north, south) ends of the section and loosing oxygen toward the middle of the section as the waters became progressively older. On this basis the oldest water in the oxygen poor layer would seem to be in the vicinity of latitude 15°N. On the other hand, it is posible that a similar average oxygen gradient might be caused by a progressive mixing of the oxygen poor layer in section B with waters of different origins and oxygen contents. The average salinity anomaly of this stratum, as an indicator of the homogeneity of the water in question, clarifies the point.

The average salinity anomaly for the whole thickness of the oxygen poor layer was calculated from the normal temperature-salinity relationship of North Atlantic water as determined by Helland-Hansen (1930) in which:

$$S_t = 34.737 + 0.038t + 0.0029t^2$$

and salinity anomaly may be expressed by:

$$\text{S.A.} = S \text{ o/oo} - S_t \text{ o/oo}.$$

The results together with average temperature and average salinity of the oxygen poor layer are listed in table 11.[3] This table indicates that according to salinity anomaly two relatively homogeneous types of water make up the oxygen poor layer of section B. One type, with anomaly range of +0.05 to −0.08 o/oo, characterizes the water between 34°N

TABLE 11

Station	Average T°	Average S o/oo	Average S o/oo anomaly	Average O_2 cc/l	Average O_2 o/o
1159	9.51	35.30	−0.05	3.81	58.9
1160	8.45	35.30	0.05	3.92	59.0
1161	8.78	35.33	0.04	4.00	60.0
1162	9.13	35.33	0.01	3.85	59.2
1163	8.63	35.26	−0.01	3.69	56.4
1164	8.26	35.24	0.00	3.72	56.3
1165	9.28	35.32	−0.01	3.34	51.6
1166	8.11	35.29	0.06	3.58	53.6
1167	8.60	35.22	−0.05	3.19	48.4
1168	8.58	35.19	−0.08	2.96	44.9
1169	8.01	35.11	−0.11	3.13	46.8
1170	7.80	35.03	−0.17	2.82	41.8
1171	7.45	34.97	−0.20	3.02	44.6
1172	7.31	34.85	−0.31	2.90	42.9
1173	6.96	34.79	−0.34	2.98	43.8
1174	6.74	34.77	−0.34	3.03	44.1
1175	6.50	34.74	−0.36	3.18	46.2
1176	6.41	34.75	−0.34	3.37	48.7
1177	6.30	34.77	−0.31	3.27	48.8
1178	5.52	34.70	−0.32	3.71	51.9
1179	5.86	34.66	−0.39	3.68	53.0

and 18°N latitude. This range of anomaly is characterized also by an average temperature range of 8.01° to 9.51° and average salinity range of 35.19 o/oo to 35.33 o/oo, the average of the whole layer between these latitudes being 8.73° and 35.28 o/oo respectively. On the other hand, the southern part of the section, between latitudes 12° and 1°N, is characterized by a salinity anomaly of −0.31 to −0.39; the average temperature of this layer at different points between these latitudes ranges from 5.52° to 7.31°; the

[3] Ibid. Page 11.

average salinity from 34.66 o/oo to 34.85 o/oo. The mean for the whole length of the layer between latitudes 12° and 1°N being 6.45° and 34.75 o/oo respectively.

Thus, judging from the general distribution of temperature and salinity in the Atlantic it is concluded that most of the water in the oxygen poor layer north of 18°N had its origin in the North Atlantic north of latitude 50°N, whereas that of the southern part of this layer, south of 12°N was derived from the South Atlantic south of latitude 40°S. Accordingly the water which has come from the south has travelled about fifty per cent farther than that originating in the North Atlantic.

Between latitudes 12° and 18° the anomaly gradient, −0.08 to −0.31, and the average temperature and salinity range of 7.31° to 8.58° and 34.85 to 35.19 o/oo indicates a mixture of these two types of water.

The water north of 18°N which is presumed to originate in high latitudes of the north has an oxygen content which decreases, north to south, from 4.0 cc per liter to 2.96 cc per liter, 60 to 45 per cent of relative saturation, as the water becomes progressively older. Similarly the water south of 12°N latitude, which seemingly originates at the surface in high latitudes of the southern ocean, shows a decrease in average oxygen content from south to north from 3.71 to 2.90 cc per liter, 53 to 43 per cent of total saturation. If the conclusion that the water of the oxygen poor layer between 12° and 18°N latitude represents the oldest water in the section be correct it should contain the lowest amounts of dissolved oxygen, and that such is the case is shown in table 11 (fig. 39); the minimum average oxygen content of 2.82 cc per liter, 41.8 per cent of total saturation, occurs in the vicinity of latitude 15° (sta. 1170).

The Direction and Average Velocity of Drift of Oxygen Poor Layer

We have next to consider the relationship that the position of section B (fig. 1) bears to the direction of drift in the deeper part of the water column. For this information we must have recourse to general knowledge of oceanic circulation from which it is presumed that the circulation in the depths of the Atlantic is chiefly meridional (see Schumacher, 1932), and that the less deep water of the oxygen poor layer has a well developed north or south component. Thus, along section B both the water of the oxygen poor layer and the underlying water is assumed to have a well developed average component in a direction parallel to the series of stations. This brings us to the final step previous to calculating the oxygen consumption, namely to estimate the mean horizontal velocity of this component of the oxygen poor layer. Available methods for the study of water transfer in the depths of the ocean are almost entirely of an indirect nature, among these, the most applicable in the present case is that suggested by Wattenberg in 1927 (and subsequently employed by Deacon, 1933), based on the assumption that the series of waves in the oxygen curve (fig. 39) of the oxygen poor layer represent the annual maxima and minima oxygen concentrations of the water of this layer when it was at the surface. The fact that such seasonal variations do exist in the surface waters of high latitudes has been discussed previously (page 64); in a complete cycle of one year there is a maximum and a minimum in oxygen content. If then in subarctic and subantarctic regions water sinks at all times of the year, as seems probable, these maxima and minima should be propagated downward and toward the equator. Consequently the distance between two maxima or two minima as presented in the oxygen poor layer should seemingly indicate the average distance travelled by the water of that layer in a direction parallel to the series of stations of section B during one year. The closer the direction of section B corresponds to the resultant direction in which the water is moving the more nearly do the results express the average velocity of drift for the water of the oxygen poor layer. However, it must be remembered that there is little evidence at hand to indicate the principle direction of drift of the water of this layer.

It seems certain that the maxima and minima as appearing in section B (fig. 39) are not due to error of observation because the difference in amplitude between them far exceeds the titration error, and, especially, because the curves are based on average, not on individual values. Thus, in the oxygen poor layer between latitudes 29° and 15°N the difference in amplitude between a maximum of oxygen content and the next succeeding minimum for four complete phases, beginning with the most northern maximum is 0.32, 0.39, 0.63, and 0.31 cc dissolved oxygen per liter; also in the region between 1° and 11°N the difference in amplitude between a maximum of oxygen content and its succeeding minimum for three complete phases, beginning with the most southerly maximum, is 0.47, 0.35, and 0.16 cc dissolved oxygen per liter. The values and positions of the maxima and minima scaled from the average curve (fig. 39) are given in table 12.

TABLE 12

Oxygen Minima Latitude	Mean Latitude	Average O_2 cc per liter	Annual Oxygen Consumption cc/liter	cc/sq. cm.	Distance nautical miles	Velocity cms/sec	Component
31°30′		3.82					
	28°30′		0.44	9.6	360	2.1	South
25°30′		3.68					
	23°57′		0.63	37.3	186	1.1	South
22°24′		3.33					
	20°15′		0.43	36.6	258	1.5	South
18°06′		2.95					
	16°27′		0.34	36.1	198	1.2	South
14°48′		2.82					
11°06′		2.88					
	9°24′		0.31	35.5	204	1.2	North
7°42′		3.02					
	5°51′		0.42	47.1	222	1.3	North
4°00′		3.25					
Oxygen Maxima							
28°48′		4.0					
	26°39′		0.41	10.0	258	1.5	South
24°30′		3.72					
	22°36′		0.42	31.4	228	1.3	South
20°42′		3.58					
	18°36′		0.50	46.6	252	1.5	South
16°30′		3.13					
8°48′		3.04					
	7°06′		0.36	40.6	204	1.2	North
5°24′		3.37					
	3°18′		0.37	41.5	252	1.5	North
1°12′		3.72					

Data for oxygen poor layer of "Atlantis" section B. Col. 1 gives latitudes of oxygen maxima and minima (page 74, fig. 39). Col. 2 their mean latitudes and col. 3 the average oxygen content of oxygen poor layer at positions in col. 1. Results of consumption calculations tabulated in cols. 4 and 5 were calculated according to method described on page 78. Col. 6 expresses distance between successive maxima and successive minima from which results of col. 7 were calculated for the component parallel to section B (page 74), the north or south direction being given in col. 8. Table is divided into two parts, one part based on oxygen minima and the other on oxygen maxima.

In conjunction with the occurrence of oxygen minima and maxima in the oxygen poor layer of section B it appeared of interest to determine if this phenomenon was by any chance peculiar only to that layer of water, marked out on the basis of its relative oxygen content (see page 8), or whether the same phenomenon existed for a water layer from approximately the same depths but bounded by some hydrographic characteristic, such as two isotherms. Consequently the average oxygen content was determined for the whole thickness of the water layer between the 5° and 15° isotherms at each station of section B. And plotting the results against latitude shows that a series of maxima and minima exist (fig. 40) which correspond quite clearly with those characterizing the oxygen poor layer. Hence we can eliminate any suspicion that the maxima and minima are peculiar to the oxygen poor layer.

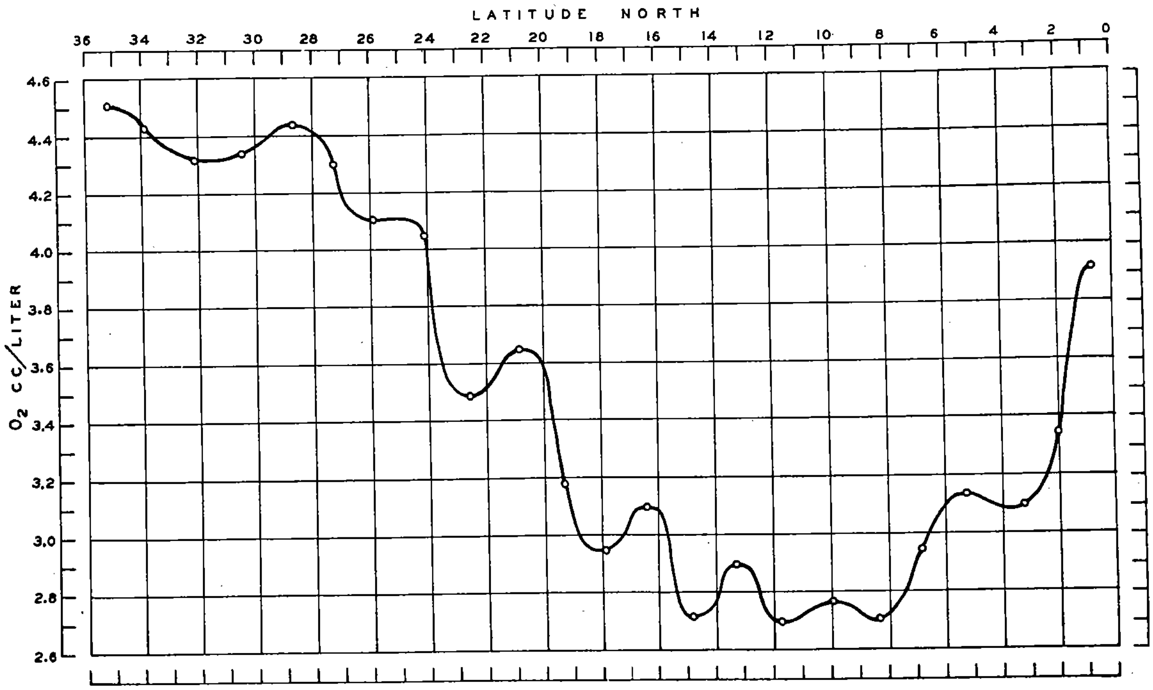

FIG. 40.—Average oxygen content of layer between 5° and 15° isotherms of "Atlantis" section B.

The distances between successive maxima and successive minima, north of latitude 15°N in section B, indicate an average velocity in the oxygen poor layer ranging from 1.1 to 2.1 cms per second (186 to 360 nautical miles per year) for the apparent southerly component; south of 11°N an average velocity of 1.2 to 1.5 cms per second (210 to 252 nautical miles per year) for the apparent northerly component (fig. 41). Steps in this calculation are given in table 12.[15]

[15] Deacon (1933) has calculated the north component of the Antarctic intermediate layer on the basis of the oxygen maxima and minima occurring at the depth of the salinity minimum in the South Atlantic. According to him the north component increases from a velocity of 1.3 miles per day at 40°S to 2.5 miles per day at 7°S. Between 40°S and 20°S a velocity difference amounting to less than $\frac{1}{5}$ mile per day is obtained based on the greater distance between successive maxima than successive minima. Deacon believes this difference to be due to water which sinks in winter flowing at first more rapidly than that which sinks in summer. While the explanation may be correct it does not appear that such small differences in velocity as brought out by this method of calculation would be significant.

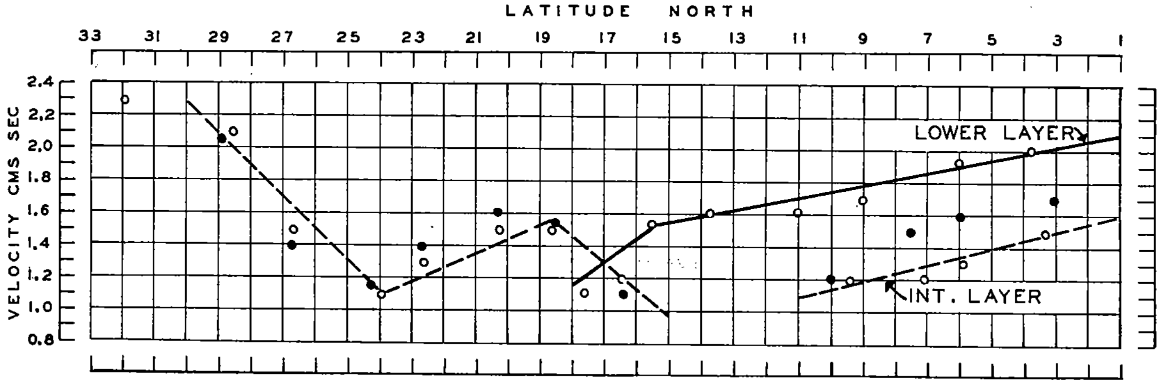

FIG. 41.—Average velocities (cms/sec) of drift parallel to "Atlantis" section B for oxygen poor layer (broken line), rich underlying layer (to 2000 meters depth, solid line) and 5°–15° layer (solid circles).

Similar calculation for the 5°–15° layer of section B (page 76) yields average horizontal velocities ranging from 1.1 to 2.3 cms per second north of 15°N and 1.1 to 1.6 cms per second south of 11°N (fig. 41). Thus, by similar calculation velocities of the oxygen poor layer and the 5°–15° layer are almost identical for the same geographical positions.

CALCULATION OF THE ANNUAL CONSUMPTION OF DISSOLVED OXYGEN IN THE OXYGEN POOR LAYER OF SECTION B

Granted that the above assumptions and conclusions are correct and that the sinking surface water of the convergence zones of high latitudes acquires approximately the same maximum and minimum concentrations of oxygen in each year we may now proceed to a tentative calculation of the annual oxygen consumption from the oxygen poor

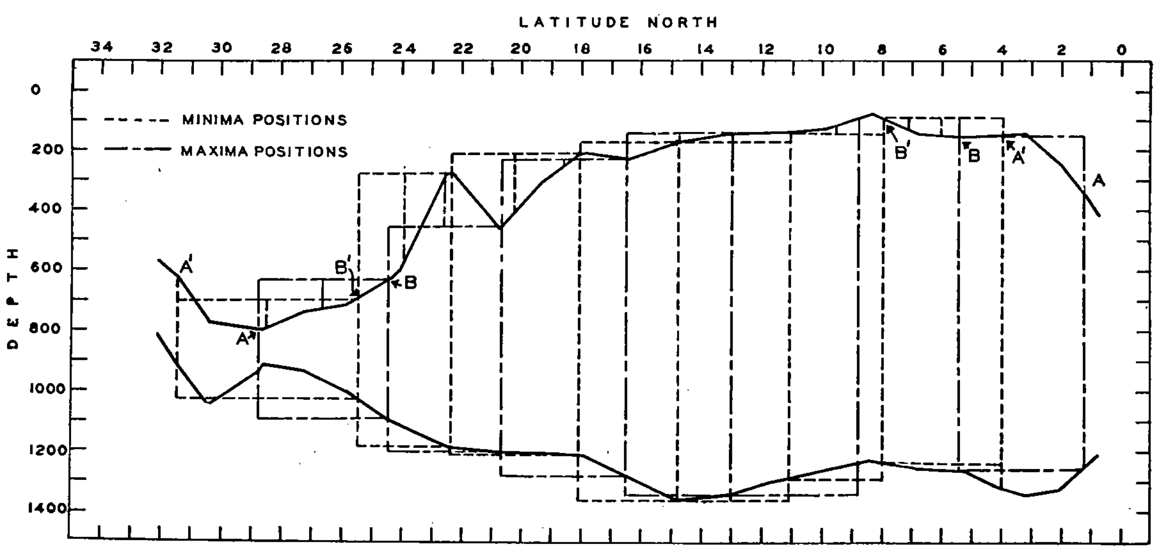

FIG. 42.—Diagram of method used in calculating oxygen consumption in oxygen poor layer of "Atlantis" section B.

layer. The results of oxygen consumption are expressed here in two ways: the consumption per unit volume of water and per unit area of surface. The calculation does not express the total amount of oxygen consumed in this layer because oxygen supplied from sources other than the horizontal currents having maximum north south components are neglected. These are considered later (page 81).

Consumption per Unit Volume

This calculation may be made roughly by taking the difference in oxygen content per unit volume between two consecutive maxima or two consecutive minima. However, as the oxygen poor layer is of varying thickness a more precise result is obtained by subtracting the average oxygen content per unit volume (cc per liter) at each maximum and at each minimum from the average content of the same horizontal stratum of water at the position of the maximum or minimum (as the case may be) next in the direction in which the oxygen values are higher. This calculation (fig. 42) was carried out for each half of section B, divided as described previously (page 74). The results give the average amount of oxygen consumed per unit volume in one year as the water of the oxygen poor layer moves from the position of one maximum (or one minimum) to that of the next. The horizontal layer included in the calculation at the position of a given maximum (maximum A, for example, in fig. 42) does not always coincide exactly with the total thickness of the oxygen poor layer at that position, particularly is this true in the northern half of the section where the thickness of the oxygen poor layer is rapidly increasing toward the south (fig. 6; page 16). In the southern half of the section the agreement between the water columns at two positions is closer as the oxygen poor layer is of more uniform thickness. The calculation has been carried out for each maximum and each minimum lying between 31° 30′N–14° 48′N and 10° 54′N – 1° 12′N and the results (table 12) are assumed to represent the average consumption of oxygen per unit volume per year in the oxygen poor layer at a series of points midway between every two maxima and two minima.

Consumption per Unit of Surface Area

The areas of each of the parts of the oxygen poor layer inclosed between every two maxima and every two minima (thus the areas overlap and more points are obtained; fig. 42) were measured first with a planimeter. Each of these smaller areas, in terms of unit volumes, was then multiplied by the average oxygen consumption per unit volume (calcalculated as above) and the result, after division by the horizontal distance between the two maxima (or the two minima) which inclose it, is assumed to give the average annual consumption of oxygen per unit of surface area. These results are expressed in table 12 as the average annual consumption of dissolved oxygen for each section of the oxygen poor layer inclosed between the positions of two successive maxima or two successive minima.

Results of Consumption Calculation

According to these calculations the annual oxygen consumption within the oxygen poor stratum of section B ranges from 0.34 to 0.63 cc per liter north of latitude 15°N, and from 0.31 to 0.42 cc per liter south of 11°N (table 12). Thus, from 10 to 18 per cent of the oxygen present in the layer appears to be consumed each year by organic oxidations in situ.

Oxygen consumption per unit area of surface is more variable as it depends both upon the consumption per unit volume and on the thickness of the oxygen poor layer. The calculations show it as ranging from 9.6 to 46.6 cc per square centimeter of surface annually north of latitude 15°N and from 35.5 cc to 47.1 cc south of latitude 11°N (table 12). The lowest consumption values occur north of 24° 30'N, where the oxygen poor layer is less than 500 meters thick.

OXYGEN CONSUMPTION FROM REMAINDER OF THE WATER COLUMN OF SECTION B EXCLUSIVE OF OXYGEN POOR LAYER

It is necessary to estimate the amount of oxygen disappearing from the other parts of the vertical water column (upper oxygen layer and rich underlying layer, page 8) if the total annual oxygen consumption in the whole water column is to be determined.

In the upper oxygen layer where an abundant supply of oxygen is maintained principally by turbulent movements of the water it is impossible to calculate consumption by the method used for the oxygen poor layer because of local enrichments. The relative importance of oxygen consumption in the upper stratum to the total consumption in the whole water column is discussed in a later chapter (page 82). On the other hand, in the oxygen rich underlying layer the supply is maintained principally by horizontal currents (as in the oxygen poor layer) and as other requirements for theoretical analyses are fulfilled its oxygen consumption can be calculated as above.

Average Oxygen Gradient and Determination of Velocity of Drift of Underlying Oxygen Layer

For convenience the underlying oxygen layer has only been considered to a depth of 2000 meters; variations in oxygen content below this depth are small, and the amount of oxygen disappearing from the deepest parts of the water column over long periods of time is believed to be very small.

The average oxygen content shows a definite north south gradient; it decreases both from the northern (5.51 cc per liter, 76.5 per cent saturated) and southern (5.44 cc per liter, 75.2 per cent saturated) ends of section B to a minimum (4.92 cc per liter, 68.3 per cent saturated) between 19° and 16°N latitude (fig. 43). Thus, the minimum region lies several degrees further north than it does in the overlying oxygen poor layer.

On the basis of the nature of the average oxygen gradient and on the assumption that the average drift of the underlying oxygen layer (to 2000 meters depth) has a directional component parallel to section B (page 74) it appears that north of 19°N the average horizontal component is southerly and south of 16°N it is northerly. Also as a series of the so called oxygen maxima and minima[16] (fig. 43) are present, the average velocity for the northerly component between the approximate latitudes of 16°N and 1°N is estimated to be between 1.5 and 2.0 cms per second[17] (table 13). This is about 0.5 cms

[16] In the lower layer of section B to a depth of 2000 meters, the difference in amplitude between the minima and following maxima from 3° 12'N to 19° 12'N latitude are 0.35, 0.36, 0.35, and 0.20 cc of dissolved oxygen per liter.

[17] In connection with this estimation of the average northerly component it is interesting that Defant (1932), at "Meteor" station No. 254 (2° 28'S, 34° 57'W), observed a mean northerly component of 6.0 cms per second and an easterly component of −10.0 cms per second at 2000 meters; the resultant direction was calculated to be N 59°W with a velocity of 12 cms per second.

per second higher velocity than that estimated for the average northerly component of the oxygen poor layer (page 76). North of 18°N the oxygen maxima and minima in the average oxygen curve are less well defined than further south.

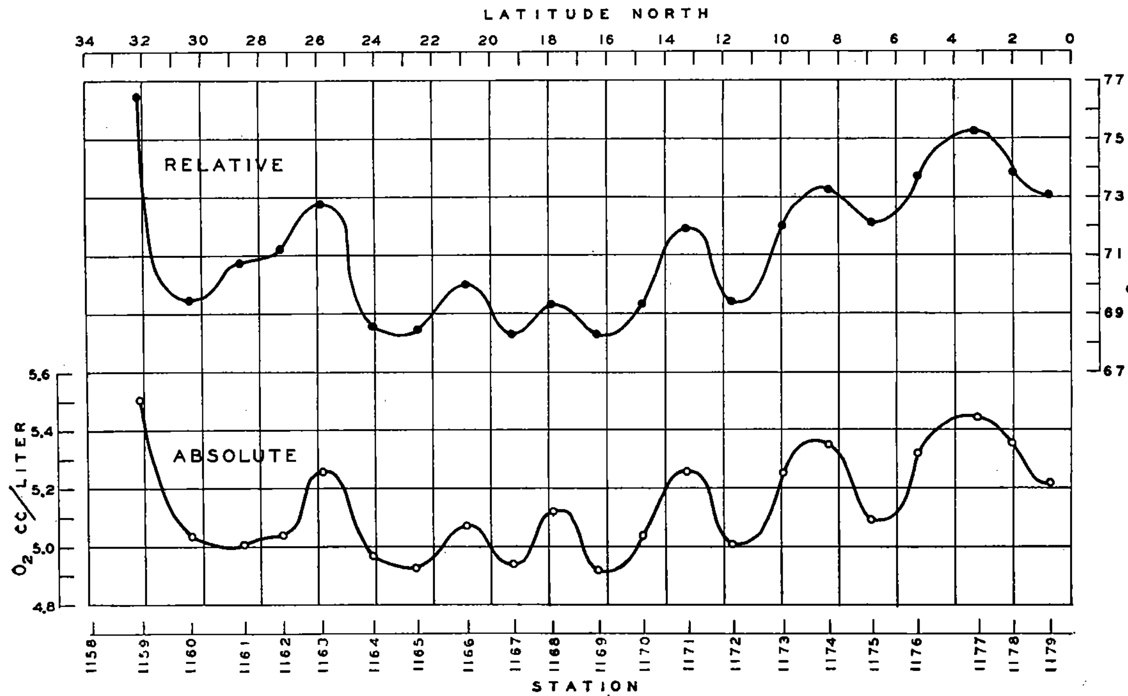

FIG. 43.—Average oxygen content of rich underlying oxygen layer to 2000 meters depth.

ANNUAL UTILIZATION OF OXYGEN FROM THE UNDERLYING OXYGEN LAYER

Using the same method of calculation as for the oxygen poor layer (page 77) gives the following results. Between latitudes 18° and 1°N the oxygen utilized per unit volume of water varies from 0.08 to 0.13 cc per liter annually with an average of 0.103 cc per liter, and the utilization per unit area ranged from 5.68 to 9.36 cc per square centimeter of surface with an average of 7.47 cc (table 13). This represents an annual consumption of about two per cent of the total oxygen present in the underlying layer to 2000 meters depth.

TABLE 13

Oxygen Maxima Latitude	Mean Latitude	Average O_2 cc per liter	Annual Oxygen Consumption cc/liter	cc/sq. cm.	Distance nautical miles	Velocity cms/sec	Component
3°12′		5.44					
	5°57′		0.08	5.68	330	1.94	North
8°42′		5.36					
	11°00′		0.10	7.10	276	1.62	North
13°18′		5.26					
	15°30′		0.13	9.36	264	1.55	North
17°42′		5.13					
Oxygen Minima							
0°54′		5.21					
	3°45′		0.12	9.18	342	2.01	North
6°36′		5.09					
	9°00′		0.09	6.53	288	1.69	North
11°24′		5.00					
	13°42′		0.09	6.25	276	1.62	North
16°00′		4.91					

Data for rich underlying oxygen layer of "Atlantis" section B. Col. 1 gives latitudes of oxygen maxima and minima (page 79, fig. 43), col. 2 their mean latitudes and col. 3 the average oxygen content of the rich underlying oxygen layer (to 2000 meter depth) at positions in col. 1. Results of consumption calculations tabulated in cols. 4 and 5 were calculated according to method described on page 77; col. 6 expresses distance between successive oxygen maxima and successive oxygen minima from which results for col. 7 were calculated for the component parallel to section B (page 79); the north or south direction being given in col. 8. The table is divided into two parts, one part based on oxygen minima and the other on oxygen maxima.

TRANSFER OF OXYGEN BY EDDY CONDUCTIVITY FROM THE UNDERLYING TO POOR OXYGEN LAYER

Before proceeding to calculate the total annual consumption of oxygen from the whole vertical water column it is necessary to estimate the extent to which oxygen disappearing from the underlying oxygen layer is transported upward into the oxygen poor layer where it is then utilized. From the general vertical distribution of oxygen (page 14; fig. 7) it is apparent that turbulent movements of the water will cause an upward transfer of oxygen from the rich lower oxygen layer into the oxygen poor layer, the amount of the transfer will depend on the coefficient of eddy conductivity and the particular oxygen gradient. It has been found that the value of this coefficient for the deeper parts of the ocean ranges from about 1 to 20 C.G.S. units (Helland-Hansen, 1930; Sverdrup, 1933).

For our purposes we shall reverse the procedure and calculate a value for, A, the eddy conductivity coefficient, assuming as a working hypothesis that the entire loss in the rich underlying oxygen layer is due to vertical transport. If the value for A thus obtained falls well within the range indicated above it seems fair to assume, as the working hypothesis is reasonable, that it is entirely possible to explain the disappearance of oxygen in the deepest parts of the sea as due essentially to eddy transfer. Also we are furthermore justified in concluding that the eddy conductivity value thus obtained represents an upper limit provided the calculation of the rate of disappearance of oxygen from the deepest part of the water column is correct.

For convenience of calculation the region between 10° and 5°N (sta. 1173–1176) was selected as representative of the southern half of section B. The mean values for vertical distribution were plotted and data required were scaled from the mean curve. Since the eddy conductivity in the deeper water was assumed to be constant the coefficient may be computed by means of the formula (Defant, 1929):

$$\frac{\Delta O}{\Delta t} = \frac{A}{\rho} \cdot \frac{d_2 O}{dz^2}$$

where ΔO represents the average quantity of oxygen calculated as disappearing from the underlying layer during the time Δt (0.103 cc per liter per year $= 3.266 \times 10^{-12}$ cc per second; table 13); A is the coefficient of eddy conductivity; ρ the mean density and d_2O/dz^2 the average oxygen gradient over the distance involved.

The computation shows that a value of 8 C.G.S. units for A, the coefficient of eddy conductivity, would be required for the transfer by turbulence of all the oxygen disappearing from the underlying oxygen layer (to a depth of 2000 meters) upward into the oxygen poor layer. A similar calculation for the same data by Jacobsen's (1927) method gives a value of 9 C.G.S. units for A. Thus, 8 to 9 C.G.S. units calculated as the value of the eddy conductivity coefficient for the deeper part of the water column of the southern half of section B represents an upper limit for this coefficient provided the oxygen disappearing from the underlying oxygen layer is not greater than calculated (page 80). And, as this value lies well within the range of coefficients of eddy conductivity believed to exist in the sea, when no marked boundary surfaces are present, it seems that much of the oxygen lost from the rich underlying layer is actually transported into the oxygen poor layer, there to be consumed.

In general, the results support the view that in the sea most of the animal respiration and the oxidation of organic debris occurs chiefly above the lower boundary of the oxygen poor layer (fig. 24). But, on the other hand, it is also an established fact that some life exists throughout the whole ocean (see Hjort, 1912) and it cannot be ignored that some oxygen, even though the amount may be very small, is consumed in situ in the deepest parts of the sea. This calculation, together with the computation of the horizontal velocities of the drifts of the two deeper oxygen layers, seems to show that in the region of investigation the low oxygen content of the midstratum as compared with that of the underlying water is the result of greater oxidation, and not of a slower renewal of oxygen (page 65).

ANNUAL OXYGEN CONSUMPTION FOR THE WHOLE WATER COLUMN

For reasons previously discussed calculation of the oxygen disappearing from the water mass has been made only for underlying and oxygen poor layers. The remaining part of the water column (upper oxygen layer) is subjected to local aerations so that the effects of oxidations in situ are masked and calculation of consumption by the methods described is not possible. However, if it be possible to select a region where the upper oxygen layer is very thin then the oxidations occurring within that layer are only of small importance to the total mass and can be neglected for a first approximation of the total consumption in the vertical water column.

This condition is best met for section B in the region between latitudes 14° and 3°N where the upper oxygen layer is only 75–150 meters thick (fig. 6). And, as the oxygen poor layer is here from 1250 to 1350 meters thick, it appears unlikely that more than 10 per cent of the total oxygen consumed in the whole water column comes from the upper layer.

Thus, as the annual oxygen consumption from the oxygen poor layer, between 14° and 3°N, ranged from 35.5 to 47.1 cc per square centimeter of surface, the average being about 39.3 cc per square centimeter of surface (table 12), and that disappearing from the underlying oxygen layer averaged about 7.5 cc per square centimeter of surface per year (table 13), the total oxygen disappearing from the two layers shut off from the air can be assumed to amount to approximately 47 cc per square centimeter of surface per year. If this amount be increased by 10 per cent, to approximate the consumption in the thin upper layer, we arrive at a total consumption for the whole water column in the tropical western North Atlantic of about 52 cc of dissolved oxygen per square centimeter of surface per year.

DEPTH OF SIGNIFICANT OXYGEN UTILIZATION IN THE WATER COLUMN

On the basis of the above discussion the lower boundary of the oxygen poor layer (lower 60 per cent isoline) may be assumed to mark out the lower limit to which the principle biochemical activity in the sea extends, in so far as that activity is reflected by the oxygen distribution. The depth of this boundary, dependent both on the age of the water and on the vertical distribution of density varies from 400 to more than 1300 meters, although throughout most of the region the depth is between 900 and 1300 meters (fig. 24). It is only in the region of the American coastwise convergence that the depth decreases from 900 to 400 meters in east west direction paralleling a similar decrease in depth of other isolines (page 41). The 5° isotherm is usually just below the lower boundary (except the southern part of section B; page 44), even in the coastwise convergence where the depth of the boundary is only 400 meters. This fact indicates that the vertical distribution of biochemical oxidations in the water column is to a considerable extent controlled by the vertical distribution of temperature and density (page 37).

In order to classify the groups of water in the sea from a biochemical standpoint a conventional grouping similar to the trophosphere and stratosphere of Defant (1928) may be convenient. In this case the terms biotrophosphere and biostratosphere are suggested; the former to include the part of the water column of significant biochemical activity, extending from the surface to the lower boundary of the oxygen poor layer (fig. 24), and the latter comprising the deeper parts of the water column.

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