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The hydrography of the Gulf of Venezuela *

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One of the very distinguished contributions of HENRY B. BIGELOW to the subject of oceanography is his study of the hydrography, plankton, and and fishes of the Gulf of Maine. It is the most complete description and analysis which exists of any circumscribed body of coastal water. Because of its breadth of outlook and high technical standard, this work is a model for studies in marine ecology. It is appropriate to contribute to this volume in Professor BIGELOW's honour a sketch of the hydrographic conditions which are found in another gulf of somewhat similar proportions, but under far different influences than those which dominate the Gulf of Maine.

Summary—The distribution of salinity, temperature, oxygen, and total phosphorus in the Gulf of Venezuela is described.

The physical circulation appears to consist of two estuarine cells. The first is generated by the outflow from Lake Maracaibo, which terminates in a mixing zone over the sill off Calabozo Bay, where the water which occupies the deeper basin of the Bay is formed. The second is fed by water formed in this mixing zone which escapes seaward after mingling with more saline water drawn in from subsurface layers of the Caribbean.

The semi-diurnal components of the tide are augmented by resonance in the Gulf of Venezuela, and with the wind account for the vertical mixing which occurs over the sill of Calabozo Bay.

The trade winds, which predominate in winter, produce large seasonal differences in mean sea level across the Gulf, and control the distribution of the brackish water as it moves seaward from the outlet of Lake Maracaibo. Upwelling, which occurs in the lee of the Peninsula of Paraguana, is accompanied by an accumulation of phosphorus and a depletion of oxygen in the deep water near the coast. Similar conditions are found in the basin of Calabozo Bay.

The influence of countercurrents on the biochemical circulation is discussed.

THE GULF of Venezuela lies in the seaward extension of the syncline which forms the Maracaibo Basin. It opens directly on the deep water of the Caribbean Sea, and carries into it the entire outflow from Lake Maracaibo. This is the most substantial accession of fresh water along the Venezuelan coast of the Caribbean, and is estimated at 21 billion cubic metres per year. The northeast trades blow steadily along the axis of the Gulf from December through April. The annual range in temperature is small, being about 2° C at Maracaibo. Being situated in 12° N latitude the Corioli parameter is weak. Differences in salinity and the winds thus dominate the hydrography of the Gulf.

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The Gulf may be divided into two parts: the Outer Gulf and Calabozo Bay. These regions are separated by a sill with depths of 18 metres, extending along the 71st meridian. West of the sill a basin 28 metres in depth occupies the northern half of Calabozo Bay. East of the sill the bottom of the Outer Gulf slopes downward to provide depths of 40 to 80 metres over a considerable area. Access to the Gulf is probably limited to Caribbean water from depths not greater than 100 metres (Fig. 1).

The only earlier observations on the Gulf of which I am aware are measurements of

Fig. 1. Bathymetric chart of Gulf of Venezuela. Based on H.O. No. 5520—Depths in metres

surface salinities across the Gulf in December 1953 by GESSNER (1953 B, 1955), and a few records of chlorinity off the entrance to Lake Maracaibo by the Corps of Engineers, U.S. Army (1938). Undocumented statements relative to the water of Lake Maracaibo and its approaches, and on tide levels in the Gulf, are based on information secured by the Woods Hole Oceanographic Institution in the course of studies which it is expected to publish subsequently. These studies were made for the Creole Petroleum Corporation, which has graciously consented to the use of this information. The outflow of Lake Maracaibo was estimated from climatological data by DOUGLAS B. CARTER of the Johns Hopkins University Laboratory of Climatology (CARTER, 1954).

The greater part of the data to be discussed was secured by the *Atlantis* between December 7 and 9, 1954. Three sections across the Gulf and two extending seaward from the adjacent capes provide information on the distribution of temperature, salinity, oxygen, and total phosphorus content (Fig. 2). I am greatly indebted to L. V. WORTHINGTON and W. G. METCALF who secured this data and to NATHANIEL CORWIN who analyzed the samples for total phosphorus, using the method of HARVEY (1948).

The data secured by the *Atlantis* are presented in Figs. 3 to 6, which show the distribution of the variables in the five sections occupied. Fig. 7 shows their distribution in a section along the axis of the Gulf.

Fig. 2. Position of hydrographic stations, sections and tide stations

THE PHYSICAL CIRCULATION

The Axial Circulation

The more general features of the circulation are shown by the distribution of properties along the axis of the Gulf (Fig. 7). The distribution of salinity is especially informative, since the fresh-water outflow from Lake Maracaibo serves as an indicator of the water movements.

In Calabozo Bay the circulation is estuarine. Along the western shore the outflow from the Lake produces a thin layer of brackish water of salinity less than 15°/₀₀. As this water moves seaward the salinity of the surface layer increases gradually to about 30°/₀₀ over the sill. A rather sharp halocline at about 15 metres separates the surface layer from water having salinities greater than 30°/₀₀ which occupies the deeper basin.

Over the sill, and on its seaward slope, there appears to be a zone of effective mixing, in which the surface water from the Bay mingles with the Caribbean water from the Outer Gulf. In this zone the salinity increases from 30 to >35°/₀₀ and does not vary greatly with depth. On one side this mixing zone produces the bottom water of

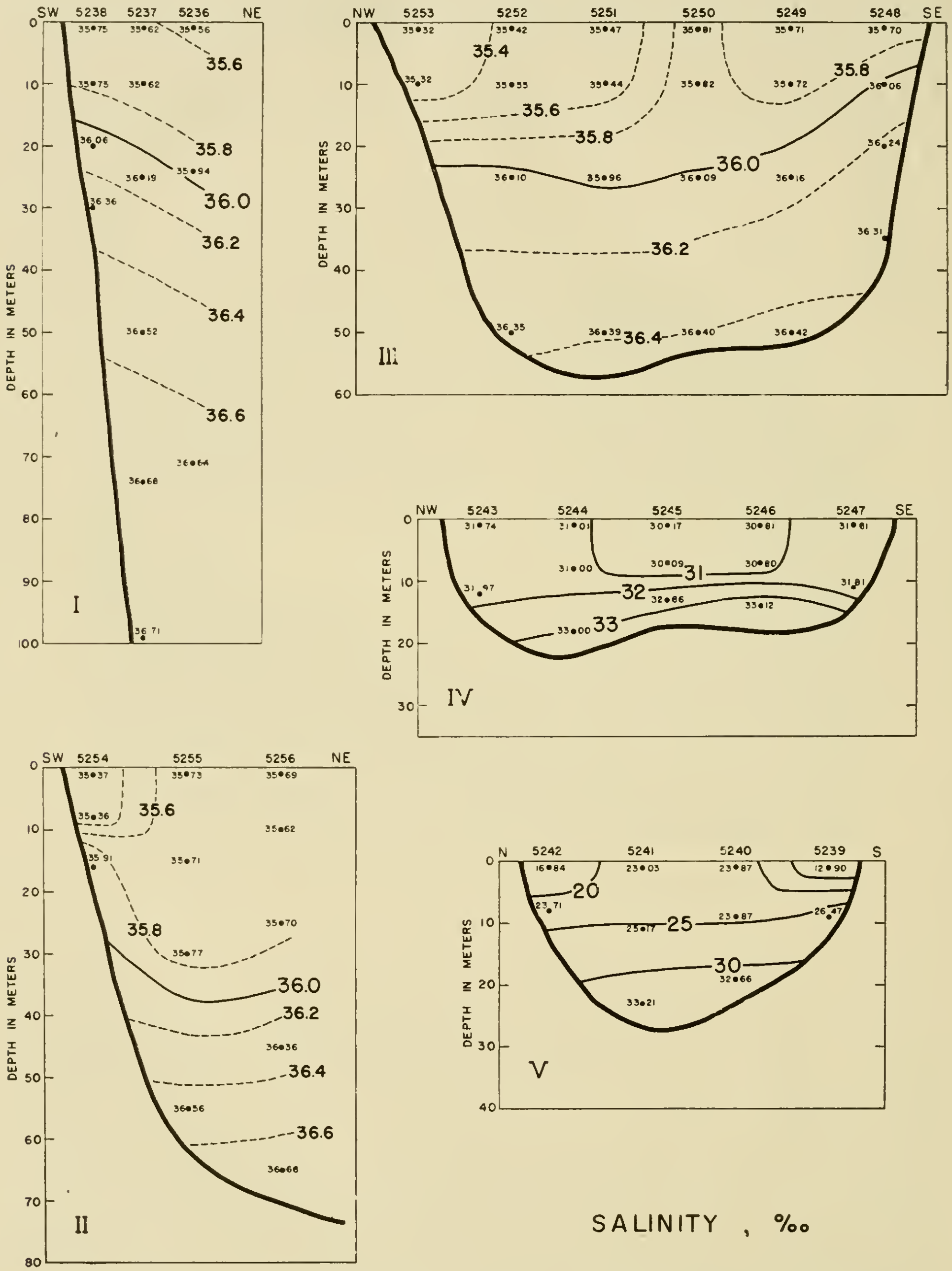

Fig. 3. Distribution of salinity in Sections I–V, Gulf of Venezuela. See Fig. 2 for positions

Calabozo Bay which, flowing westward as a countercurrent, supplies the salt consumed in diluting the outflow from the Lake. On the other side it produces a mixture so similar to the superficial layers of the Caribbean that its identity can be recognized only with difficulty.

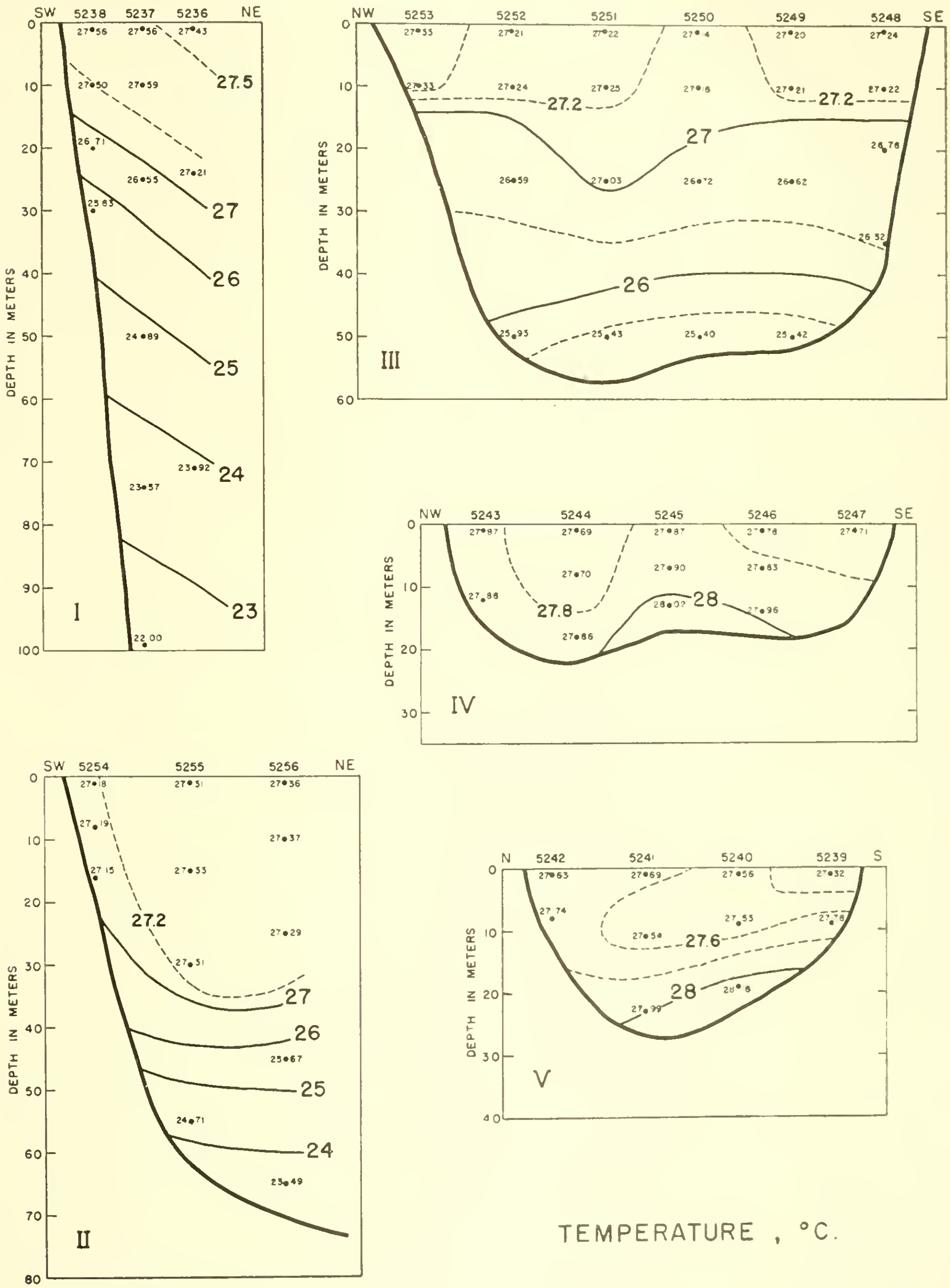

Fig. 4. Distribution of temperature in Sections I–V, Gulf of Venezuela. See Fig. 2 for positions

The distribution of temperature supports the above interpretation. The coolest surface water is found in the brackish outflow from the Lake. The surface water of Calabozo Bay warms as it moves toward the sill, where the warmest water and an almost uniform vertical distribution of temperature is found. The water of Calabozo

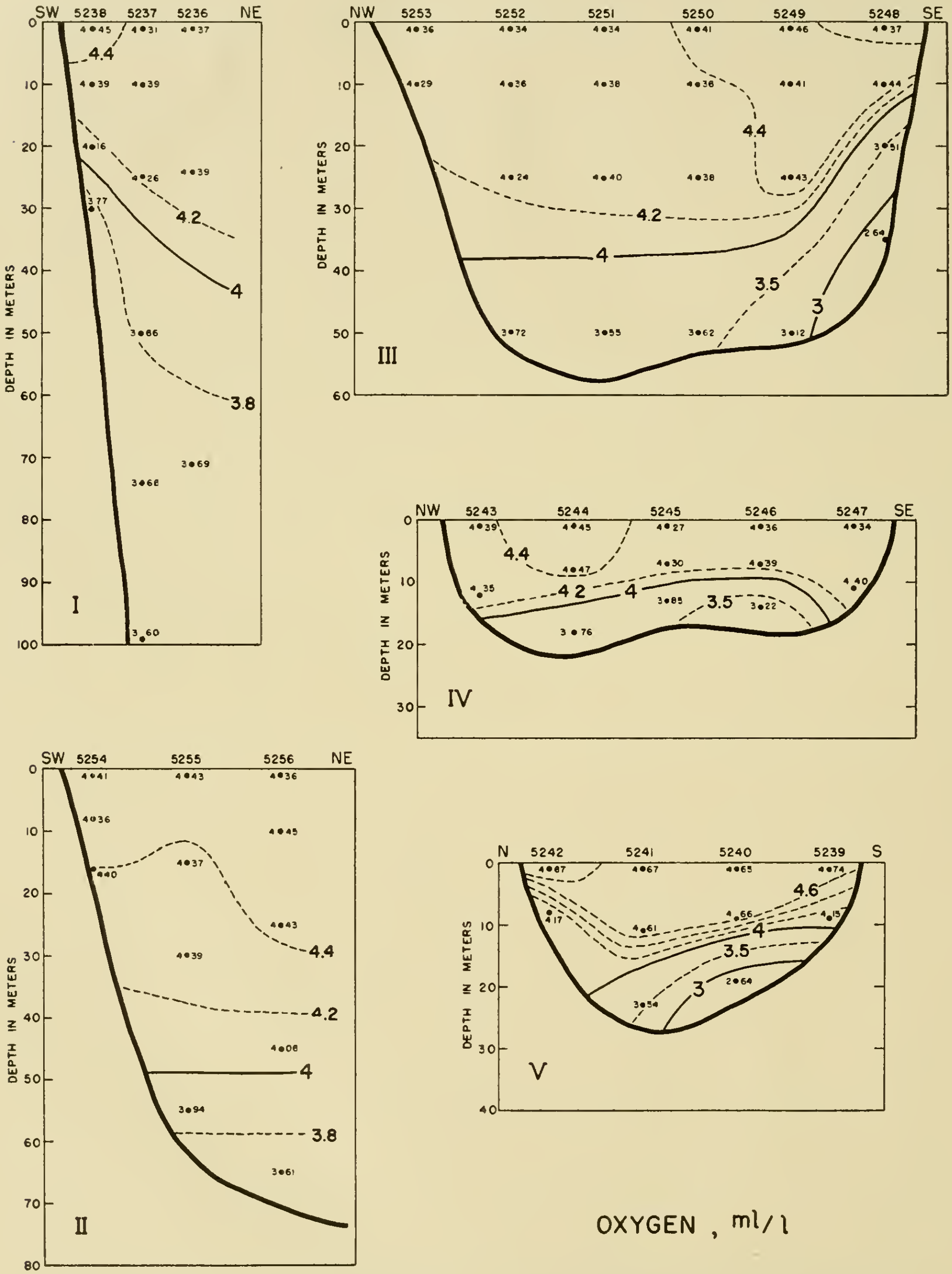

Fig. 5. Distribution of oxygen in Sections I–V, Gulf of Venezuela. See Fig. 2 for positions

Bay below the halocline is warmer (>28° C) than any other water in the region. This water cannot have arisen by direct advection from the deeper water of the Outer Gulf, which is colder and more saline.

Data from the files of the U.S. Hydrographic Office show that the mean monthly

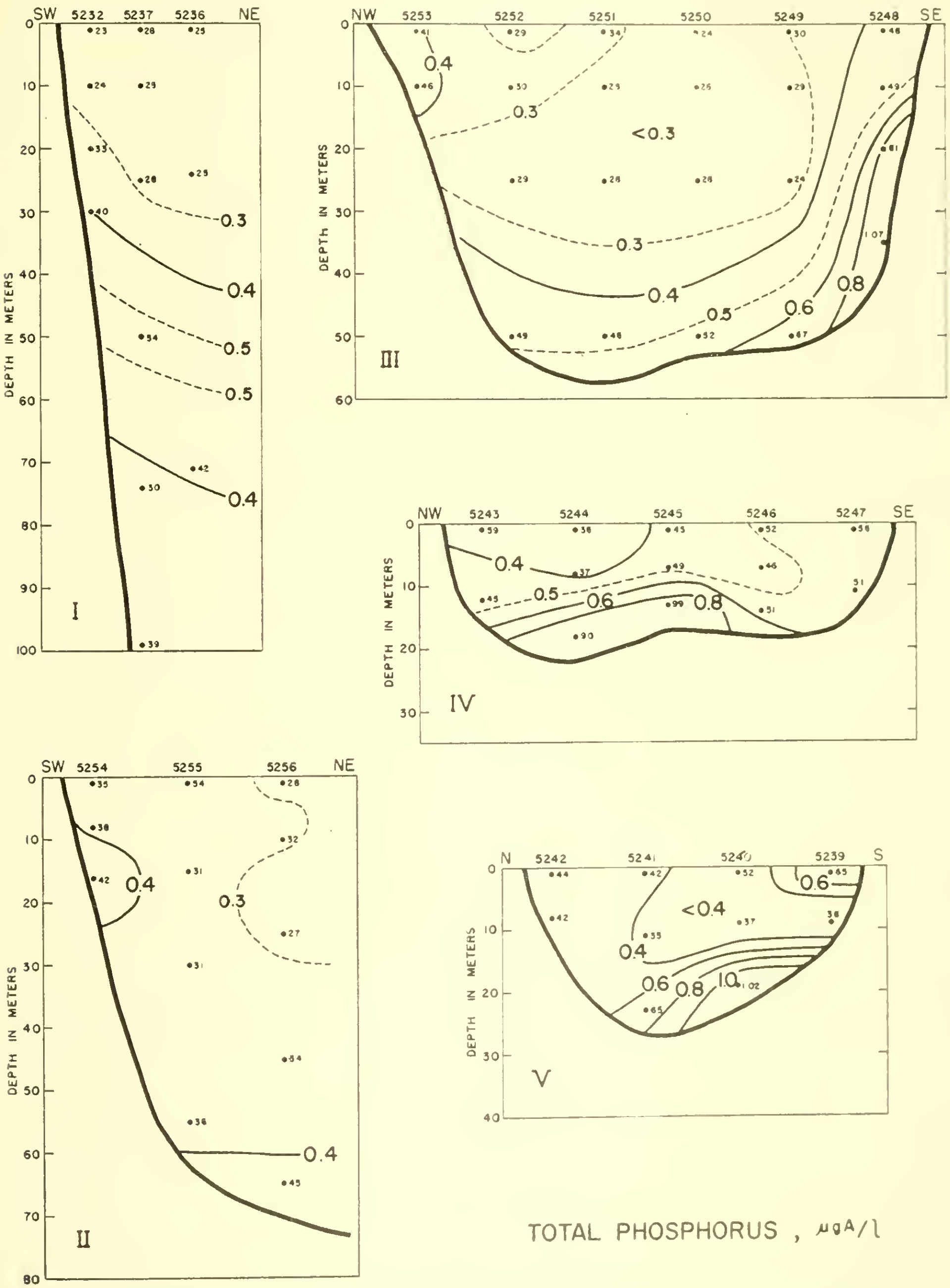

Fig. 6. Distribution of total phosphorus in Sections I–V, Gulf of Venezuela. See Fig. 2 for positions

temperature of the surface water of the Outer Gulf is at a maximum of 28·2° C in October, and falls to a minimum of 25·3° C in February. In December the mean value is 27·0° C, corresponding closely to the present observations. The high temperature of the deeper water of Calabozo Bay may be considered to have been acquired some months previously, when this water was formed in the mixing zone over the sill.

The distribution of phosphorus and oxygen also shows the stratification arising from the estuarine circulation of Calabozo Bay, the similarity of the water in the Outer Gulf to that in the Caribbean, and the independence of the deeper water of Calabozo Bay from that east of the sill. These properties are dependent on biological processes as well as on the physical circulation, and will be considered in more detail below.

The Horizontal Circulation

The distribution of properties in the several sections across the Gulf (Figs. 3–6) and in the surface diagrams (Figs. 8–11) shows no evidence that the brackish outflow from Lake Maracaibo is deflected to the right by the Corioli force, as is so frequently the case in the estuaries of higher latitudes. The water of low salinity formed at the outlet of Lake Maracaibo occupies a crescentic band along the western margin of Calabozo Bay (Fig. 8). The eastward extent of this band along the southern shore of the Gulf is not defined by the data. Along the northern shore it terminates abruptly in a convergence at 71° 30′ W. The Secchi disk showed an abrupt change in the transparency of the water across this convergence. This general distribution is reflected by the temperature and phosphorus content of the surface water.

Observations by the Corps of Engineers, U.S. Army (1938) show a northwesterly set of the alongshore currents off the outlet of the Lake, supporting the view that surface water is being transported at that point toward the western end of the Bay. The Sailing Directions for the West Indies (U.S. Navy Hydrographic Office, 1949) on the other hand state that a current, which sets south-westerly along the coast of the Peninsula of Guajira, turns eastward to flow along the southern coast of Calabozo Bay as far as Punta Penas (70° 30′ W), where it turns northward and is dissipated in the middle of the Gulf. A south-westerly set is described along the eastern shore of the Outer Gulf. This account indicates a convergence on the side of the Gulf opposite to that inferred from the *Atlantis* observations.

It seems probable that the north-east trade winds drive the brackish water formed at the outlet of Lake Maracaibo into the western end of the Bay, and tend to hold it against the shore. Escape is affected by alongshore currents, as discussed by LIVINGSTONE (1954). These currents appear to follow the coast of the Peninsula of Guajira until it turns northward, where they meet water moving into the Gulf along that shore, and both currents are deflected toward the middle of the Bay. Doubtless complex eddies exist throughout the Bay, but no pattern is revealed by the observations, nor any special path by which the fresh water works its way seaward. It may be that, as the trade winds slacken in summer, the brackish outflow from the Lake turns eastward under the Corioli influence, and sets up the pattern described in the Sailing Directions.

Although the water in the Outer Gulf resembles that in the Caribbean closely, small differences in temperature and salinity reveal the final steps in the escape of lake water to the Sea. Upwelling appears to occur along the Paraguana coast, as shown by the slope of the isohalines in Sections I and III, Fig. 3. This gives rise to a band of surface water having salinities higher than that found offshore, which extends north-

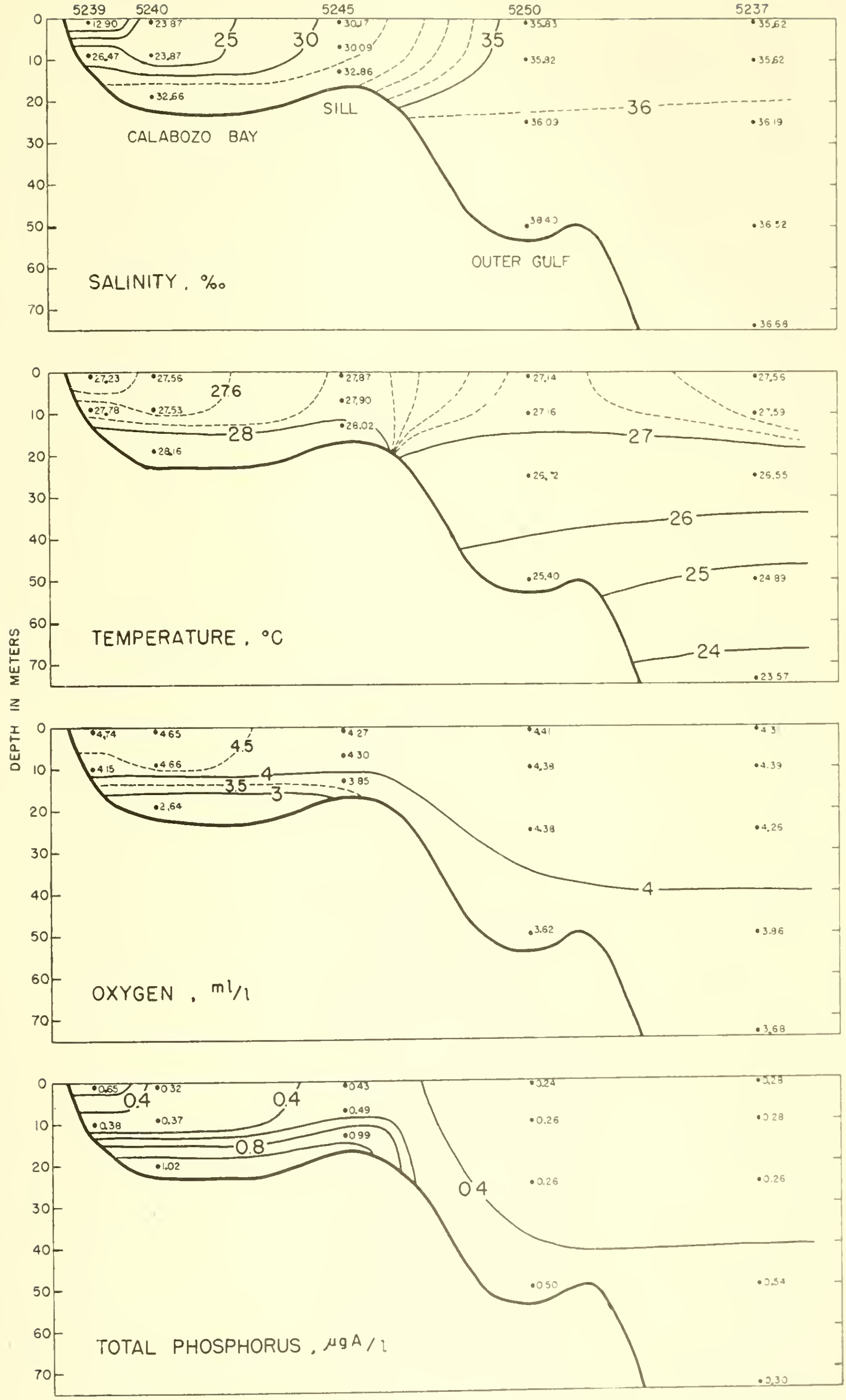

Fig. 7. Distribution of salinity, temperature, oxygen, and total phosphorus in Section A–A along axis of Gulf of Venezuela. See Fig. 2 for positions

westward from the Peninsula of Paraguana. It provides a component which, when mixed with water from Calabozo Bay, forms a mass of water slightly colder and less saline than the water of the Caribbean. This mass may be traced as it flows westwards close to shore around the Peninsula of Guajira (Fig. 8). The Sailing Directions report a westerly set of 1·75 knots off this headland during the greater part of the year.

In summary, the physical circulation of the Gulf of Venezuela appears to consist of two estuarine cells, separated by a transition zone of vertical mixing. The surface outflow of the inner cell is fed by water escaping from Lake Maracaibo, and is consumed in the mixing zone over the sill. This zone is the source of the deep counter-

Fig. 8. Salinity at 1 metre depth in Gulf of Venezuela

current which provides salt to the surface outflow. The outer cell, less clearly defined, is fed by the water formed in the mixing zone, which escapes seaward at the surface after mingling with water from a countercurrent drawn in from the subsurface layers of the Caribbean. In both cells the surface drift is displaced to the left, under the influence of the wind.

The estuarine cell of Calabozo Bay finds its counterpart in many bays of the eastern coast of North America. Aside from the quantitative effects of the controlling topography, the more general difference in the circulation arises from the dominant effect of the prevailing wind on the horizontal flow in Calabozo Bay, as compared to the Corioli effect in the estuaries of higher latitudes.

Along the Atlantic coast the bays and estuaries discharge into, and lose their identity in producing, a broad band of coastal water of reduced salinity which separates the coast from the full sea water of the ocean. Along the Venezuelan shore a distinct band of coastal water is lacking, and Caribbean water in full strength penetrates the Gulf of Venezuela. The front separating the bay water from the full sea water is the mixing zone over the sill of Calabozo Bay. The water in this zone may be considered to be the rudimentary counterpart of the coastal water of the Atlantic coast.

If this view be accepted, the outer cell of the circulation of the Gulf of Venezuela finds its counterpart in those processes taking place along the margin of the Gulf

Fig. 9. Temperature at 1 metre depth in Gulf of Venezuela

Stream and in the slope water, by which the coastal water of the Atlantic coast becomes incorporated and lost in the general circulation of the ocean.

Tides

The tides at Aruba, like those of the Caribbean in general, are of the mixed type in which the diurnal constituents predominate. The diurnal range of tide is 0·8 feet. In contrast, at Zaparita Island, off the mouth of Tablazo Bay, the tide is predominantly semi-diurnal and the mean range is 3 feet. The dimensions of the Gulf of Venezuela are such that the semi-diurnal constituents are augmented by resonance to a high degree, while the diurnal constituents are relatively unaltered.

A comparison of the harmonic contents of the tides (Table I) shows that the M_2 component at Aruba precedes that at Zapara Island by 123° or more than one-quarter period. High water occurs at Las Piedras only one-half hour earlier than at Zaparita Island, and 1·3 hours earlier than at Zapara Island. These relations place the antinode

Fig. 10. Total phosphorus at 1 metre depth in Gulf of Venezuela

Table I
Tidal harmonic constants, U.S. Coast and Geodetic Survey (1951)

Constituent		*Greenwich Epoch (G)* Aruba	*Greenwich Epoch (G)* Zapara I	*Amplitude (H) feet* Aruba	*Amplitude (H) feet* Zapara I
Diurnal	K_1	241°	247°	0·3	0·24
	O_1	228°	246°	0·2	0·15
	P_1	241°	243°	0·1	0·08
	Q_1	—	244°	—	0·02
Semi-diurnal	M_2	161°	284°	0·13	1·04
	S_2	84°	217°	0·07	0·11
	N_2	282°	248°	0·03	0·32
	K_2	—	268°	—	0·03
Sum—Diurnal amplitudes				0·6	0·49
Semi-diurnal amplitudes				0·23	1·50
Ratio of sums				2·7	0·33

for the semi-diurnal tides across the entrance to the Gulf at a longitude intermediate between Aruba and Las Piedras. The amplitude of the M_2 component is increased eightfold, and the sums of the semi-diurnal components sixfold as the result of the resonance.

Fig. 11. Oxygen under saturation at 1 metre depth in Gulf of Venezuela

Since enough water must cross the sill of Calabozo Bay, having a depth of 18 metres, to raise and lower the level of the Bay nearly one metre twice daily, it is evident that strong tidal currents are to be expected over the sill. These currents, combined with the wind, account for the mixing which appears to occur in this region.

Water Levels

The monthly mean tide levels at Las Piedras change by as much as 0·8 feet in the course of the year (Fig. 12, A). The pattern is similar to that observed at positions on the Atlantic coast south of Chesapeake Bay and in the Gulf of Mexico (MARMER, 1951), and evidently is part of widespread phenomena. The monthly mean tide levels at Zaparita Island follow a similar pattern, but the annual variation in level is only 0·4 feet.

The mean annual difference in water level across the Gulf of Venezuela, between Las Piedras and Zaparita Island, is 0·92 feet in a distance of 93 nautical miles. The difference in level varies with the season, being highest (1·1 ft.) in January, and lowest (0·6 ft.) in October (Fig. 12, B).

The seasonal difference in levels across the Gulf is clearly related to the prevalence of north-easterly winds, as shown by wind data from Maracaibo (Fig. 12, D). The difference in levels may be explained in part by the reduced density of the water at the head of the Gulf. The magnitude of the difference is, however, so great as to raise a question as to the precision of the levelling between Las Piedras and Zaparita Island. There can be little doubt, however, that the mean tide level at Zaparita is one-half foot greater, relative to the level at Las Piedras when the north-east trades are at a maximum, than it is when their influence is reduced. Clearly winds which affect the slope of the sea surface so greatly are adequate to produce the effects on the circulation which have been deduced from the hydrographic observations.

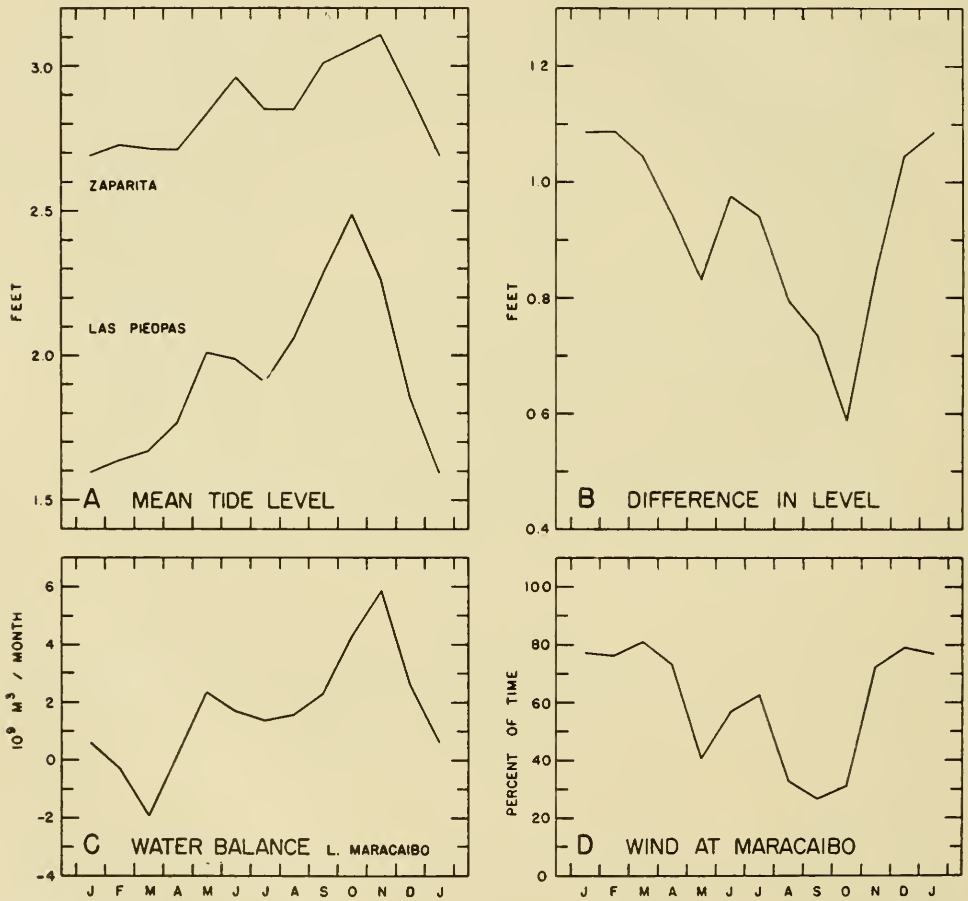

Fig. 12. *A*. Monthly mean tide levels. Average at Las Piedras for 1942–49 and at Zaparita Island for 1940–53. Data from Bar Survey, Maracaibo

B. Difference in average monthly mean tide level at Las Piedras and Zaparita Island

C. Average monthly net water balance of Lake Maracaibo. Estimated by CARTER (1954)

D. Per cent of time wind blew from N through ENE at Maracaibo, 1952. Data from Bulletin Bimensureal, Servicio de Meteorologia y Communicaciones, Ministerio de la Defensa, Fuerzas aereas, Maracay

Seasonal Influences on the Hydrography

The available data on the waters of the Gulf were collected in December. While there is no information on the conditions at other seasons, the annual variation in the two factors which control the circulation is known, and may be used to indicate the direction, if not the degree, in which the pattern will change with the season.

The rainy season in the Maracaibo Basin extends from April to December. The observations were consequently made at a time when the quantity of fresh water in the Gulf is maximal. During the following four months the outflow from the Lake is reduced and may come to an end (Fig. 12, C). The salinity of Calabozo Bay may consequently be expected to increase, and the hydraulic forces which drive its estuarine circulation to weaken. These tendencies should be reversed beginning in April. A rough estimate indicates that the quantity of fresh water present in Calabozo Bay in December is equivalent to about two years' outflow from the Lake. It is probable consequently that in the four months of the dry season the change in the mean salinity will be limited.

The effect of the north-east trade winds in maintaining the anticyclonic circulation in Calabozo Bay should continue through the winter. With the reduction in outflow from the Lake, the continued wind-induced motion will mix the water, and reduce the vertical and horizontal differences in salinity.

After April the winds become more variable and slacken in intensity. As the summer progresses, increasing outflow from the Lake should restore the salinity stratification. With the weakened effect of wind, the brackish water should spread more diffusely across the Bay. Possibly the Corioli force overcomes the wind influence and causes the escaping water to follow the southern shore to the eastward in the latter part of summer.

THE BIOCHEMICAL CIRCULATION

The distribution of the major elements in sea water, which determine the salinity, is the result of purely physical processes of advection and mixing. It may be used, consequently, to trace the general circulation of the water. In contrast, the distribution of those elements which are present in limited quantity, and which enter into the composition of organisms, may be profoundly influenced by biological activity. In particular, elements such as phosphorus and nitrogen, which become incorporated into the substance of the phytoplankton growing in the surface layers of the sea, tend to be carried downwards by the sinking of organisms, and are liberated at depth by the ultimate oxidation of the organic matter. There is thus a circulation of elements of biochemical importance which is different from that of the water itself, and of its biologically inert components.

In the case of the Gulf of Venezuela, data on the total phosphorus and oxygen content are available for an examination of the biochemical circulation.

Total Phosphorus

The total phosphorus content of water includes the phosphorus present as inorganic phosphate ions, as organic compounds present in solution, and as components of suspended organisms.

The total phosphorus content of the Gulf is higher than that of the source waters from the Caribbean. This is due primarily to the high phosphorus content of the water from Lake Maracaibo, which is on the average about 1·4 μgA per litre, whereas the Caribbean water contains about one-quarter this amount. The general pattern of distribution of salinity and phosphorus in the surface waters (Figs. 8 and 10), and in the axial section (Fig. 7), are so similar as to suggest that both properties vary as the result of the system of circulation which mixes waters derived from the Lake and Sea.

In the deeper parts of Calabozo Bay and the eastern side of the Outer Gulf, concentrations of phosphorus occur which are too great to be accounted for by the physical circulation (Figs. 6 and 7). In the former case the high salinity excludes an origin from lake water; in the latter the high phosphorus content precludes Caribbean water as the source. It is concluded that organisms and particulate matter have sunk into these basins, carrying down from the surface layers the phosphorus which has accumulated at depth.

Oxygen

In the Gulf of Venezuela the surface water, as well as that at greater depths, was everywhere under-saturated, in amount varying from 1·4 to 9·6 per cent. Physically this implies that the oxygen pressure was positive across the surface, and that oxygen was diffusing downward into the water. This condition cannot be explained by the cooling and consequent under-saturation of the surface, as is the case in higher latitudes in winter (REDFIELD, 1948), because the annual range in temperature is too small. It must be attributed to biochemical effects, arising from the excess of respiration over photosynthesis in the water.

The consumption of oxygen by respiration, in excess of its production by photosynthesis, can only persist if there is available some external source of organic matter, as is the case in waters polluted by sewage. The undersaturation of the surface waters of the Gulf of Venezuela may be the result of the high organic content of the outflow from Lake Maracaibo. In the lake water two-thirds of the phosphorus (1 μgA/l) is present in organic form, and while in the Lake much of this is probably present in living organisms capable of photosynthesis. On introduction into the Gulf, however, these organisms, which are fresh water or brackish species (GESSNER, 1953 A), may be killed by the higher salinity, and thus contribute to the quantity of organic matter immediately available for oxidation.

In support of this suggestion are the observations that the greatest under-saturation of surface water occurs in the immediate offing of Tablazo Bay (Fig. 11), and that the water of that bay is generally under-saturated with oxygen.

In the deeper parts of Calabozo Bay and the eastern parts of the Outer Gulf, where the total phosphorus was found to be anomalously high, the oxygen concentration is reduced to less than 3 ml per litre. (Compare Figs. 5 and 6). The deficiency in oxygen increases with the phosphorus content, and is about that to be expected from the increase in phosphorus if it arises from the oxidation of planktonic material (see Fig. 13). It may be concluded that the deficiency of oxygen in the deeper parts of the Gulf is due to the accumulation of organic matter as the results of the sinking of organisms and particulate matter from the surface layers of water, and that the greater part of this material has undergone oxidation.

At no place was the deeper water found to be completely devoid of oxygen. The deep circulation appears to be sufficiently rapid to prevent the accumulation of enough organic matter to exhaust the oxygen dissolved in the water. In the Strait of Maracaibo the water is flushed out each season by escaping lake water, to be replaced again with more saline water when the outflow slackens in the dry season. The oxygen content of the deeper water of the Strait is reduced to values comparable to those in the Gulf in the course of two or three months. Thus it is needless to assume that much more time is required to produce the conditions observed in the deeper parts of the Gulf.

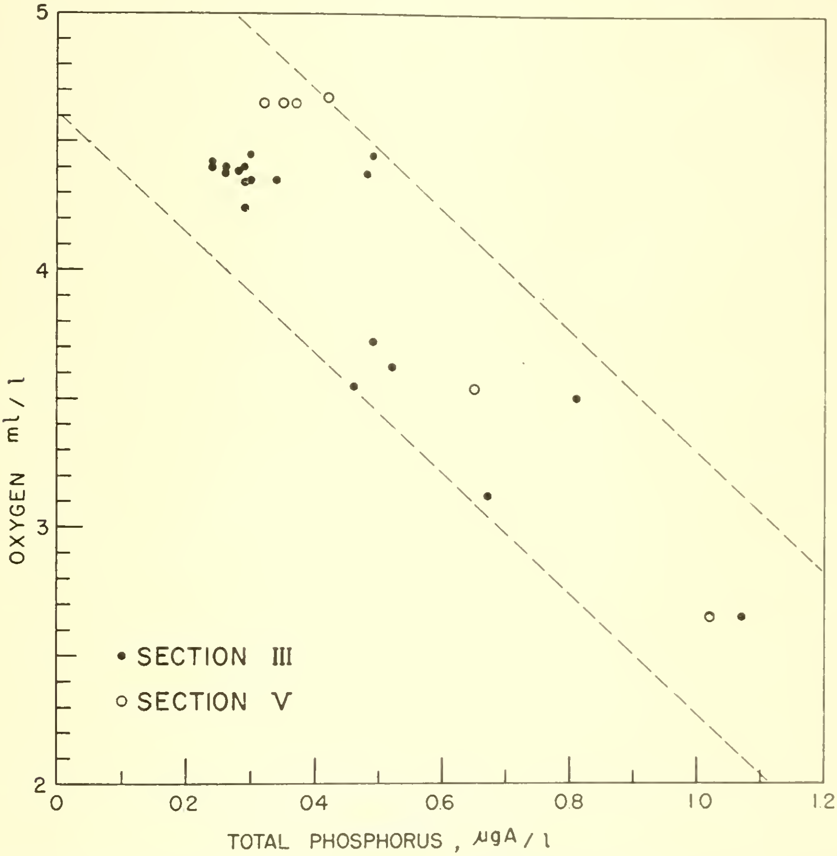

Fig. 13. Relation of oxygen and total phosphorus content of samples collected in Sections III and V. The slope of the envelopes is that required by the complete oxidation of organic matter from plankton of average composition; i.e., 2·35 ml O_2 is consumed in oxidizing organic matter containing 1 μ gA phosphorus

COUNTERCURRENT SYSTEMS AND BIOGENETIC PROPERTIES

The major ions of sea water exist in all parts of the ocean in very nearly equal proportions. It is a remarkable fact that, in contrast, most of those components which enter into the structure and chemical activity of living organisms are distributed in very different proportions in different parts of the oceans. Phosphate and nitrate, for example, are more than twice as abundant in the deep water of the Pacific and Indian Oceans than in the North Atlantic, although the concentrations of the major ions are approximately the same.

The concentrations of the organic derivative of sea water (phosphate, nitrate, and carbonate), and of oxygen, have been shown to vary from place to place in proportions related to the statistical composition of the plankton (REDFIELD, 1934). It is evident that some broad-scale process of biological origin is responsible for the distribution of these biogenetic properties in ways which are anomalous in respect to the purely physical character of the circulation.

The obvious mechanism for separating the organic derivative from the dissolved materials in one mass of sea water, and transferring it to another, is the sinking and subsequent decomposition of organisms into a deeper layer. Redistribution leading to accumulation or attenuation is then dependent on the horizontal movement of the respective layers. If such movements are consistently in opposite directions, great differences in concentrations may be developed. The counter-current principle is commonly employed in such physical mechanisms as heat exchangers. Its applications in physiology have been discussed by SCHOLANDER (1954).

The Gulf of Venezuela affords examples of two somewhat different types of counter-current system which lead to the local accumulation of phosphorus, with attendant depletion of oxygen in the deeper water.

In the Outer Gulf the winds appear to produce an offshore movement of the surface water, which is compensated for by an onshore counter-current at depth. This is referred to as upwelling. Organic matter sinking from the surface layer is carried landwards in the deep counter-current. The process leads to an attenuation of phosphorus content of the surface layer with distance from shore, and its augmentation in the deeper water which increases as the coast is approached. The degree of accumulation finally developed depends, of course, on a balance between this process and the dissipating effects of the circulation, which mixes the water vertically or transports it horizontally across the region of upwelling.

The situation in the Outer Gulf provides a small-scale example of the mechanism of enrichment of ocean water which occurs wherever trade winds give rise to upwelling along the continental coasts.

In Calabozo Bay the counter-current system of the estuarine circulation is engendered by the inflow of fresh water from Lake Maracaibo rather than by the wind. Otherwise the process leading to the attenuation of phosphorus in the surface water and its accumulation at depth is the same as in the upwelling system of the Outer Gulf. The degree of accumulation attained is limited by the rate of circulation of the deep water, which appears to move toward the head of the Bay, where it is most actively incorporated into the surface outflow. The highest phosphorus and lowest oxygen concentrations were found immediately off the outlet of the Lake.

The estuarine circulation of Calabozo Bay provides an example of a mechanism which must operate to varied degrees in many coastal embayments, fjords, and estuaries, and which may account in part for the greater fertility common to such enclosed waters, when compared to the off-lying sea.

REFERENCES

CARTER, DOUGLAS B. (1954), Report on water balance of the Maracaibo Basin. Unpublished manuscript on file, Woods Hole Oceanographic Institution.

Corps of Engineers, U.S. Army (1938), Model study of channel improvements at outer bar, Lake Maracaibo, Venezuela. *U.S. Waterways Experiment Station, Corps of Engineers, U.S. Army, Tech. Memo.* No. 106–1, 3 vols, December 1, 1938.

Gessner, Fritz (1953 a), Auf den Spuren Alexander von Humboldts in Venezuela. *Natur u. Wissenschaft*, 138 neue Zeitung, **20,** 13/14, Juni 1953.
Gessner, Fritz (1953 b), Investigaciones hidrograficas en el Lago de Maracaibo. *Acta Cientifica Venezolana*, **4** (5), 173–177, 4 figs., 4 tables.
Gessner, Fritz (1955), Die limnologischen Verhältnisse in den Seen und Flüssen von Venezuela. *Verhandl. Internat. Verein. für theoret. und angewandte Limnol.*, **12**, 284–295, 12 figs.
Harvey, H. W. (1948), The estimation of phosphate and of total phosphorus in sea water. *J. Mar. Biol. Assoc., U.K.*, **27** (2), 337–359, 11 figs., 3 tables.
Livingstone, D. A. (1954), On the orientation of lake basins. *Amer. J. Sci.*, **252** (9), 547–554.
Marmer, H. A. (1951), Tidal datum planes. *U.S. Coast and Geodetic Survey, Spec. Pub.* 135,, 142 pp.
Redfield, Alfred C. (1934), On the proportions of organic derivatives in sea water and their relation to the composition of plankton. In: *James Johnstone Memorial Volume*, Univ. Press, Liverpool, 176–192, 5 figs., 2 tables.
Redfield, Alfred C. (1948), The exchange of oxygen across the sea surface. *J. Mar. Res.*, **7** (3), 347–361, 4 figs., 3 tables.
Scholander, P. F. (1954), Secretion of gases against high pressures in the swimbladder of deep-sea fishes. II. The rete mirabile. *Biol. Bull.*, **107** (2), 260–277, 5 figs., 4 tables.
U.S. Coast and Geodetic Survey (1951), *Tidal harmonic constants—Atlantic Ocean including Arctic and Antarctic Regions*, 137 pp.
U.S. Navy Hydrographic Office (1949), Sailing directions for West Indies, Vol. II, The Lesser Antilles and the coast of Venezuela. *H.O. Pub.* 129 (6th ed.), 335 pp.