CHAPTER IV

PHYSICS AND CHEMISTRY OF GULF WATERS

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TIDES AND SEA LEVEL IN THE GULF OF MEXICO

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The feature of the tide that makes the most marked impression on the observer along the shores of tidal waters is that relating to the magnitude of rise and fall, or the range of the tide, and where the range is large the tide is indeed an impressive phenomenon, visualizing in striking fashion the ceaseless warfare between land and sea. Wide stretches of foreshore constitute the field of battle. At low water these are seemingly part of the land, but a few hours later, at high water, the invading tide claims them again for the sea.

In the Gulf of Mexico the tide exhibits no such impressive sights, for the range of tide here is small, being at most places not much more than a foot or two on the average; but what the tide lacks in impressiveness for the casual observer, it more than makes up in the variety and complexity of the phenomena it offers the investigator.

Since the Gulf of Mexico is an arm of the Atlantic it is natural to attempt to correlate the tides in the two bodies of water. Figure 23 shows the tide curves for three stations on the coast of Florida for the last 8 days of June 1948. Miami Beach is on the Atlantic coast, and Cedar Keys and Pensacola are on the Gulf coast. The vertical lines at the top of the figure indicate noon of each day. The horizontal line associated with each set of curves represents the average or mean level of the sea at each station for the 8-day period. The height of the tide at each station is shown, in feet, by the scale at the left and is reckoned from sea level.

Examining the curve for Miami Beach it is seen that high water and low water succeeded each other at intervals of about 6¼ hours so that in each tidal day (which has an average length of 24 hours and 50 minutes) there are two high waters and two low waters. The high waters rose approximately the same height above sea level as the low waters fell below it, and while the two high waters of a day, as also the two low waters, differed somewhat in height, the difference was relatively small as compared with the range of the tide which for the 8-day period averaged 2.0 feet.

At Cedar Keys, as the middle diagram shows, there were likewise two high and two low waters a day, but consecutive cycles of rise and fall differed considerably more than at Miami Beach. For example, from the first high water on the 23d to the first high water on the 24th the consecutive ranges, in feet, were as follows: 1.2, 2.3, 4.5, and 3.4. For that tidal day, therefore, the average range was 2.85 feet, but individual ranges varied from 58 percent above to 58 percent below that average value. The durations of rise and fall likewise varied considerably. On the first day they were, in hours, 5.0, 5.5, 7.7, and 6.4. For the succeeding days the differences in range and in duration diminish more or less regularly until on the last 2 days the characteristics of rise and fall at Cedar Keys are much the same as at Miami Beach.

Now it must be noted that the differences found in character of tide at the two places are in no way due to the disturbing effects of wind or weather. As will be seen later such disturbing effects do occur and result in modifying profoundly the normal features of rise and fall. The last 8 days of June 1948 were chosen for illustration precisely because of the freedom during this period of disturbing effects of wind and weather. The differences in the features of the tide at the two places for the 8-day period are due to differences in tidal character.

Examining now the tide curve for Pensacola, the difference from the other two tide curves that strikes one immediately is that at Pensacola there were but one high and one low water a day for 7 of the 8 days. In other words, the periods of rise or fall here are approximately 12 hours against 6 hours at the other two places.

Note.—H. A. Marmer died before this article was set in print. The proofs were corrected in the Division of Tides and Currents, U. S. Coast and Geodetic Survey.

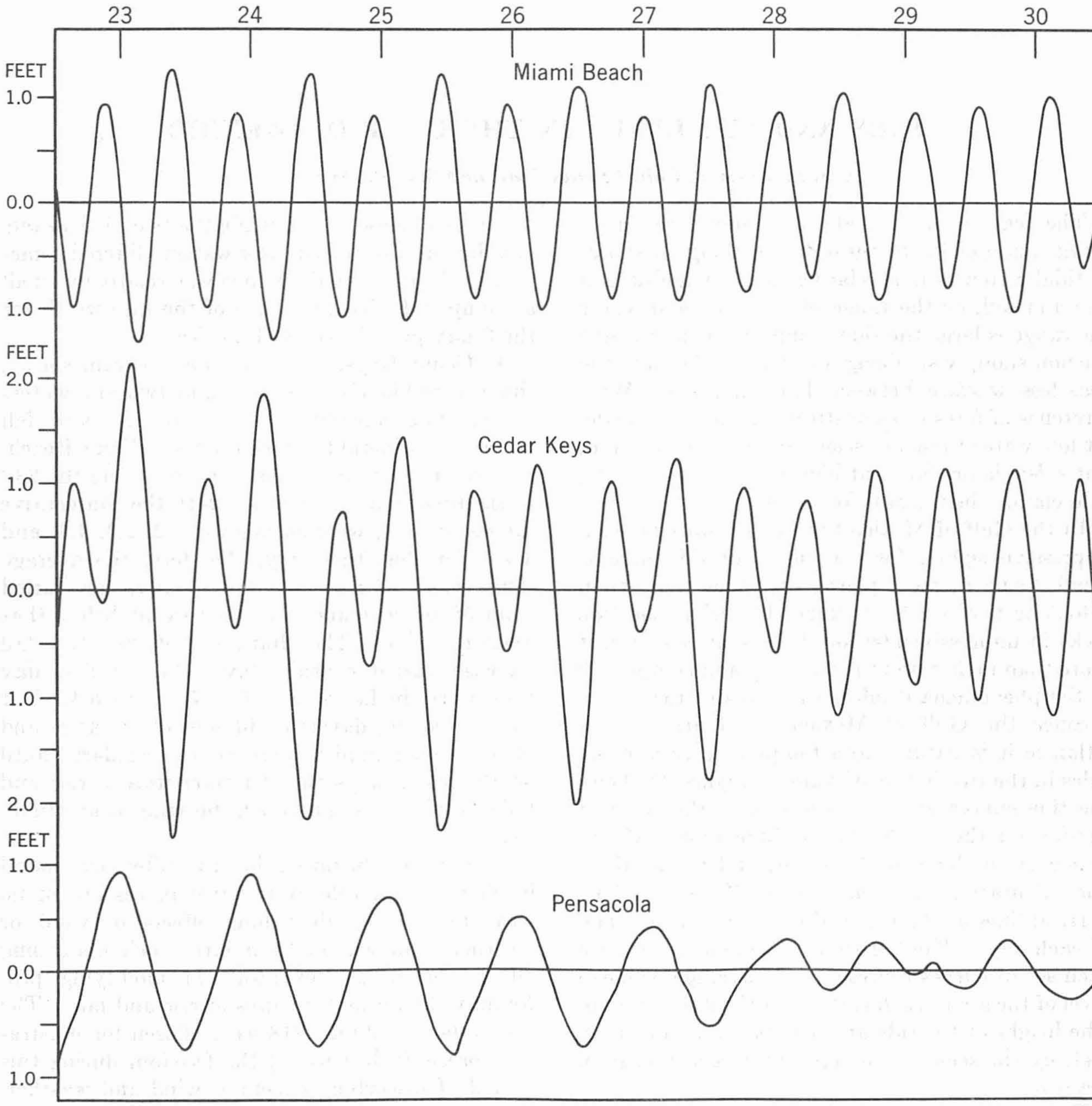

FIGURE 23.—Tide curves, Miami Beach, Cedar Keys, and Pensacola, June 23–30, 1948.

Pensacola is about 250 miles from Cedar Keys, and in this distance along the Gulf coast the tides differ strikingly. If we go up the Atlantic coast the same distance from Miami Beach, we find no such differences. In fact, in the 1,500-mile stretch from Florida to Maine, the characteristics of the tide along the Atlantic coast are much the same despite large differences in range of tide at different places. For example, at Bar Harbor, Maine, the mean range of the tide is 10.4 feet against 2.5 feet at Miami Beach. If we plot the tide curve at Bar Harbor for the last 8 days of June 1948 on a height scale one-fourth that at Miami Beach, the two tide curves would resemble each other closely.

To exemplify the character of the tide at other places in the Gulf of Mexico, we may take Key West, Florida, at the entrance to the Gulf, and Galveston, Texas, about 450 miles west of Pensa-

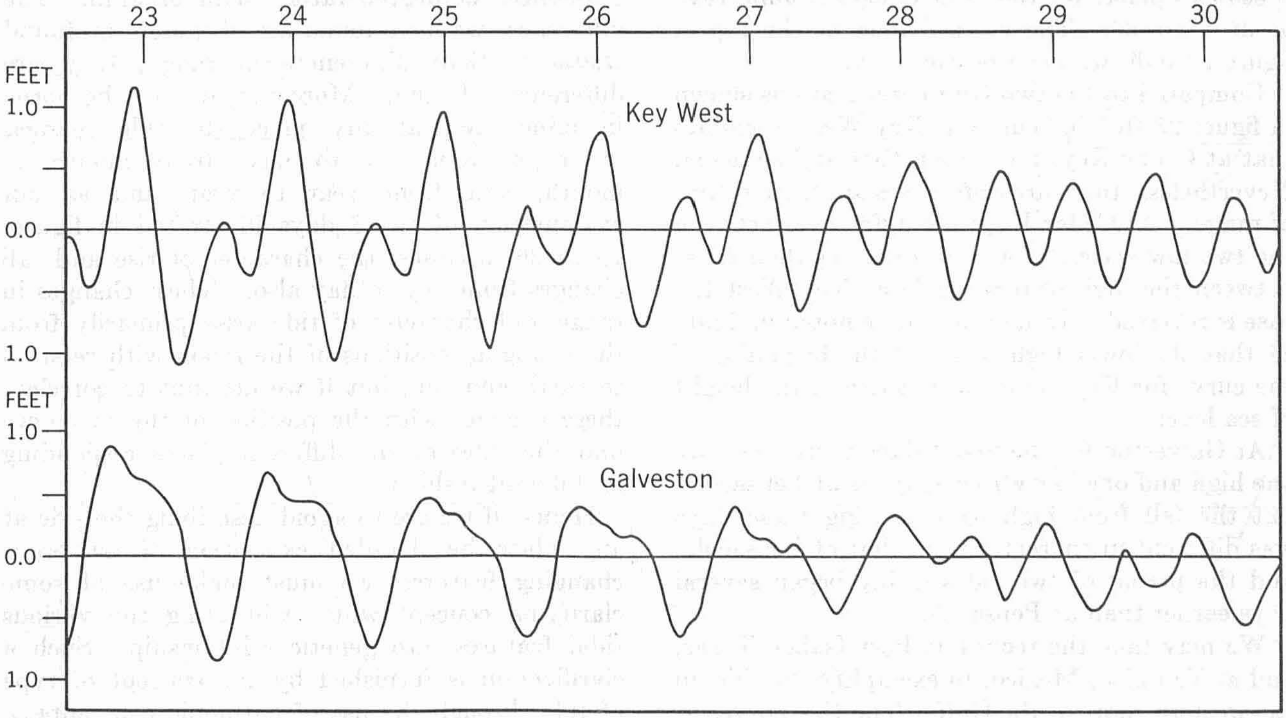

FIGURE 24.—Tide curves, Key West and Galveston, June 23–30, 1948.

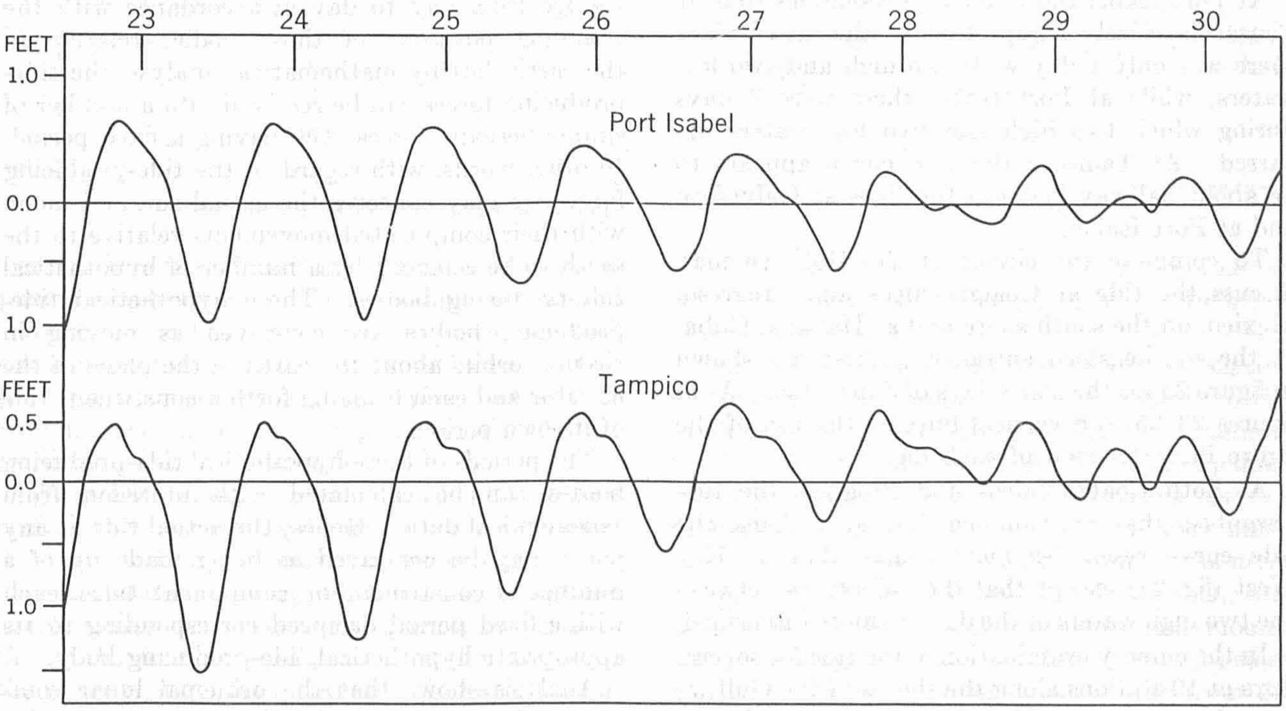

FIGURE 25.—Tide curves, Port Isabel and Tampico, June 23–30, 1948.

cola. In figure 24, are shown the tide curves for those two places for the same 8 days of June 1948 as in figure 23. The vertical lines at the top of figure 23 indicate noon of each day.

Compared to the two Gulf coast stations shown in figure 23 the tide curve at Key West resembles that at Cedar Keys more than that at Pensacola. Nevertheless, there are differences apart from that of range. At Cedar Keys the differences between the two low waters of a day are larger than those between the high waters, while at Key West the case is reversed. In fact, it will be noted in figure 24 that the lower high water at the beginning of the curve for Key West did not rise to the height of sea level.

At Galveston for the first 4 days there was only one high and one low water daily, as at Pensacola, but the fall from high water during these days was different in character from that at Pensacola, and the period of two tides a day began several days earlier than at Pensacola.

We may take the record at Port Isabel, Texas, and at Tampico, Mexico, to exemplify the tide on the western shore of the Gulf. The tide curves at the two places for the last 8 days of June 1948 are shown in figure 25. The vertical lines at the top of the figure indicate noon of each day.

At Port Isabel the tide curve resembles that at Pensacola closely except that at the latter place there was only 1 day with two high and two low waters, while at Port Isabel there were 3 days during which two high and two low waters occurred. At Tampico the tide curve appears to be about halfway between the tides at Galveston and at Port Isabel.

To complete the circuit of the Gulf we may discuss the tide at Coatzacoalcos and Progreso, Mexico, on the south shore and at Habana, Cuba, at the southeastern entrance. These are shown in figure 26 for the last 8 days of June 1948. As in figures 23–25, the vertical lines at the top of the figure indicate noon of each day.

At both Coatzacoalcos and Progreso the tide resembles that at Tampico, but at Habana the tide curve resembles most nearly that at Key West (fig. 24) except that the differences between the two high waters of the day are more intensified.

In the cursory examination of the tide for several days at 10 stations along the shores of the Gulf we have found very decided differences even though we have disregarded differences in range of tide. Differences in range of tide may be regarded as differences of degree rather than of kind. The differences we have found are of a more profound character than differences in range; they are differences of kind. Moreover, it must be borne in mind that at any place the tide changes in range from day to day, from month to month, and from year to year, and as our examination of the 8 days illustrated in figures 23 to 26 discloses, the character of rise and fall changes from day to day also. These changes in range and character of tide arise primarily from the changing positions of the moon with relation to earth and sun, but if we attempt to correlate these changes with the position of the moon we find the tides at the different places responding in different fashion.

Hence, if we are to avoid describing the tide at any place by detailed exposition of numerous changing features, we must make use of some clarifying concept which will bring the various tidal features into genetic relationship. Such a clarification is furnished by the concept of type of tide through the use of harmonic constants.

HARMONIC CONSTANTS

The tide-producing forces of sun and moon change from day to day in accordance with the changing positions of those bodies relative to the earth, but by mathematical analysis the tide-producing forces can be resolved into a number of simple periodic forces each having a fixed period. In other words, with regard to the tide-producing forces we may conceive the actual sun and moon with their complicated movements relative to the earth to be replaced by a number of hypothetical tide-producing bodies. These hypothetical tide-producing bodies are conceived as moving in circular orbits about the earth in the plane of the equator and each bringing forth a constituent tide of its own period.

The periods of these hypothetical tide-producing bodies can be calculated with precision from astronomical data. Hence, the actual tide at any place may be conceived as being made up of a number of constituent or component tides, each with a fixed period or speed corresponding to its appropriate hypothetical tide-producing body.

Analysis shows that the principal lunar component has a period of $12^h\ 25^m$ or an angular speed of 28.98° per hour. It is designated by the

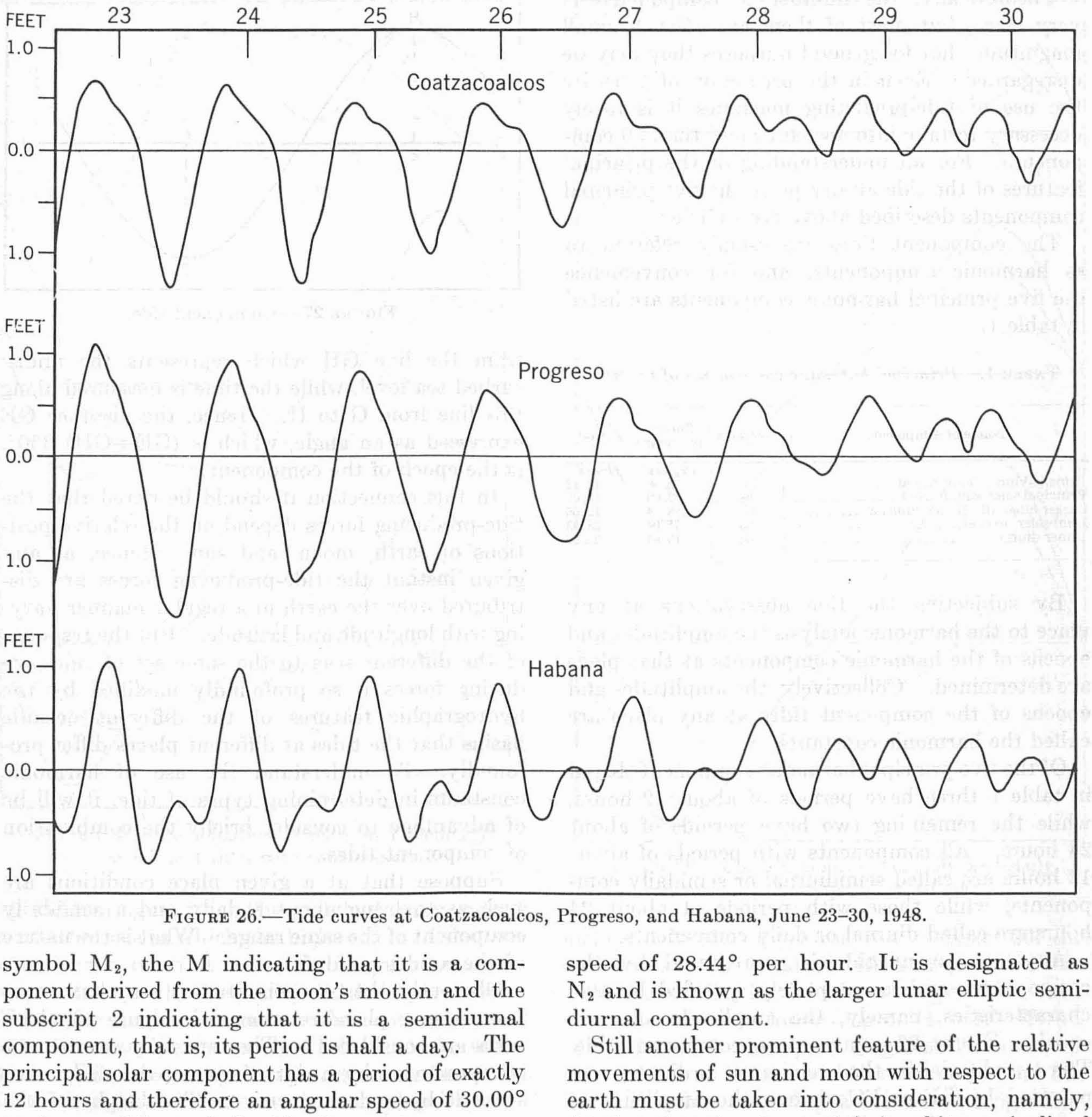

FIGURE 26.—Tide curves at Coatzacoalcos, Progreso, and Habana, June 23–30, 1948.

symbol M_2, the M indicating that it is a component derived from the moon's motion and the subscript 2 indicating that it is a semidiurnal component, that is, its period is half a day. The principal solar component has a period of exactly 12 hours and therefore an angular speed of 30.00° per hour. It is symbolized by S_2.

The actual moon does not move in a circular orbit but in an elliptical one. This means that its distance from the earth is not constant, and hence its tide-producing force varies, being less than average at apogee and greater at perigee, the period from one perigee to another being on the average, 27½ days. Analysis shows that for this reason it is necessary to introduce a simple component with a period of 12.66 hours or a speed of 28.44° per hour. It is designated as N_2 and is known as the larger lunar elliptic semidiurnal component.

Still another prominent feature of the relative movements of sun and moon with respect to the earth must be taken into consideration, namely, the fact that the planes of their orbits are inclined to the plane of the equator. This means that the declinations of sun and moon are constantly changing. It is found that two components must be introduced, symbolized by K_1 and O_1, the former arising from both the sun's and moon's tide-producing forces and called the luni-solar diurnal component and the latter arising from the moon's tide-producing force and called the lunar diurnal component.

Theoretically, the number of components is very large, but most of them are of such small magnitude that for general purposes they may be disregarded. Even in the prediction of tides by the use of tide-predicting machines it is rarely necessary to take into account more than 30 components. For an understanding of the principal features of the tide at any place the five principal components described above are sufficient.

The component tides are usually referred to as harmonic components, and for convenience the five principal harmonic components are listed in table 1.

TABLE 1.—*Principal harmonic components of the tide*

Name of component	Symbols	Speed per hour	Period
		Degrees	*Hours*
Principal lunar semidiurnal	M_2	28.98	12.42
Principal solar semidiurnal	S_2	30.00	12.00
Larger lunar elliptic semidiurnal	N_2	28.44	12.66
Luni-solar diurnal	K_1	15.04	23.93
Lunar diurnal	O_1	13.94	25.82

By subjecting the tide observations at any place to the harmonic analysis the amplitudes and epochs of the harmonic components at that place are determined. Collectively, the amplitudes and epochs of the component tides at any place are called the harmonic constants.

Of the five principal harmonic components listed in table 1 three have periods of about 12 hours, while the remaining two have periods of about 24 hours. All components with periods of about 12 hours are called semidiurnal or semidaily components, while those with periods of about 24 hours are called diurnal or daily components.

Any component tide is represented by the cosine curve and is completely specified by two characteristics, namely, the amplitude and the epoch. Figure 27 represents a component tide. The amplitude is the maximum ordinate represented by BE or FC; hence, the amplitude of a component tide is half the range of that tide. The epoch is the time, in angular measure, elapsing between the meridian passage of a hypothetical tide-producing body and the high water of its tide. In figure 27, the curve ABCD represents the rise and fall of a component tide for a complete period, A being the instant of meridian passage of the particular hypothetical tide-producing body considered. The height of this component tide at any instant is measured vertically up or down

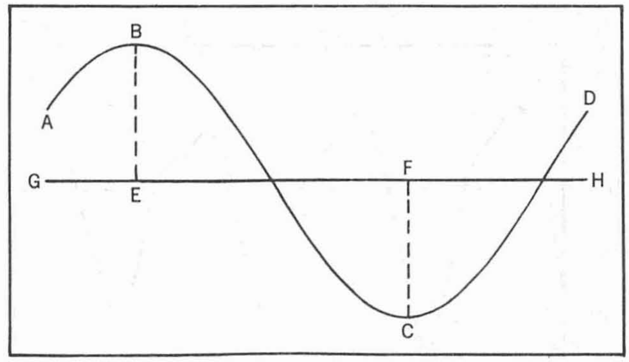

FIGURE 27.—Component tide.

from the line GH which represents the undisturbed sea level, while the time is measured along this line from G to H. Hence, the distance GE expressed as an angle, which is (GE÷GH) 360°, is the epoch of the component.

In this connection it should be noted that the tide-producing forces depend on the relative positions of earth, moon, and sun. Hence, at any given instant the tide-producing forces are distributed over the earth in a regular manner varying with longitude and latitude. But the response of the different seas to the same set of tide-producing forces is so profoundly modified by the hydrographic features of the different oceanic basins that the tides at different places differ profoundly. To understand the use of harmonic constants in determining types of tide, it will be of advantage to consider briefly the combination of component tides.

Suppose that at a given place conditions are such as to bring about a daily and a semidaily component of the same range. What is the nature of the resulting tide?

Obviously the two constituents may have various time or phase relations. In figure 28, three cases are considered. The semidaily constituent is represented by a dotted curve; the daily constituent by a dashed curve. The height of the resultant tide at any moment is clearly the sum of the heights of the constituent tides at that moment. In the figure the resultant tide is indicated by the full line curve.

In the upper diagram of figure 28, the two constituents have such time relations that their low waters occur at the same time, and the resultant tide is one in which the inequality in morning and afternoon tides is featured in the low waters and is exemplified by the tide at Cedar Keys on August

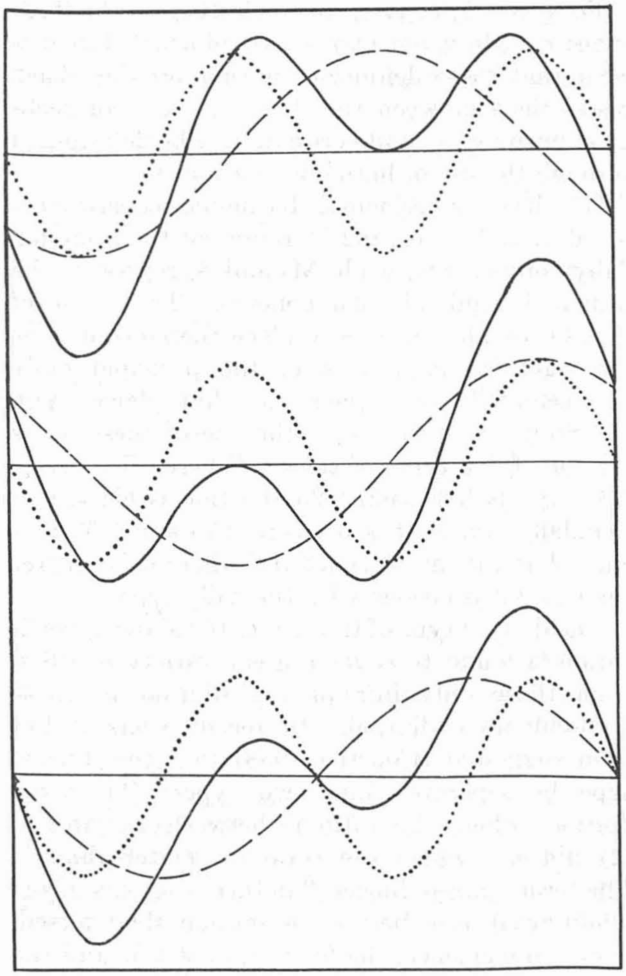

FIGURE 28.—Combination of daily and semidaily constituent tides with equal ranges.

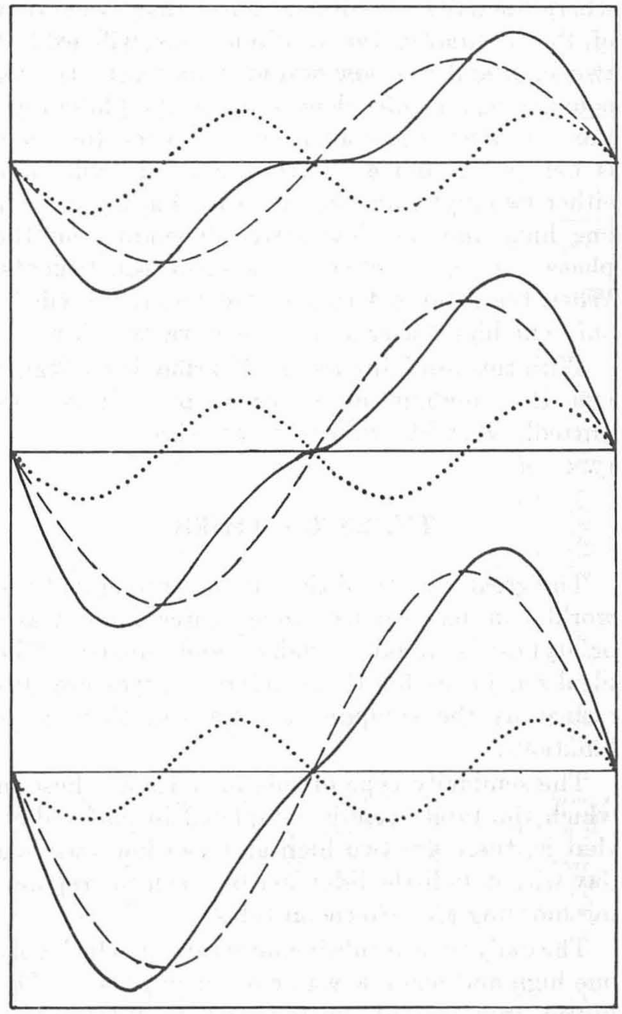

FIGURE 29.—Combination of semidaily and daily constituent tides with different ranges.

26 to 29 in figure 23. The middle diagram represents the case in which the high waters of the two constituents occur at the same time, the resultant tide featuring the inequality in the high waters. The lower diagram represents the condition when the two constituents are at sea level at the same time. The inequality is now distributed equally in the high and the low waters, exemplified by the tide at Key West on August 26 and 27 in figure 24.

Thus far, we have considered only the combination of component tides of equal ranges. What is the character of the tide resulting from the combination of daily and semidaily components of unequal ranges?

In figure 29, three cases are considered, the time or phase relations between the two constituents remaining the same, the two constituents being taken so that they are at sea level at the same instant. In the upper diagram of figure 29, the daily constituent is taken with a range twice that of the semidaily, in the middle diagram the ratio is 3 to 1 and in the lower diagram 4 to 1. With a ratio of 2 to 1, the upper diagram shows the resultant tide to be one with but one high and one low water but featuring a relatively long stand halfway between high and low water. With increasing ratios, that is with relatively larger daily constituents, the stand becomes shorter and shorter as the middle and lower diagrams show. With a ratio of 4 to 1 the resultant curve approximates the shape of the daily constituent.

If in figure 29 the time relations between the two components were taken differently, the shapes of the resultant tides would be somewhat different. Without going into further detail it is clear that where the daily constituent is less than twice that of the semidaily, the resultant tide will exhibit two high and two low waters a day with the inequality in the tides depending on the phase relations between the constituents. When the ratio is between 2 and 4 the resultant tide will have either two high and two low waters a day or only one high and one low water depending on the phase relations between the two constituents. When the ratio is 4 to 1 or greater, there will be only one high water and one low water a day.

With this brief discussion of harmonic constants and the combination of constituent tides, admittedly sketchy, we are in a position to discuss types of tide.

TYPES OF TIDES

The great variety of tides found throughout the world can be grouped under three large classes or types: semidaily, daily, and mixed. The idealized forms for these different types are furnished by the component tides and their combinations.

The semidaily type of tide includes all those in which the tidal cycle is completed in half a day; that is, there are two high and two low waters a day with only little difference between corresponding morning and afternoon tides.

The daily type of tide includes tides in which only one high and one low water occur in a day. The mixed type of tide includes those tides which feature two high and two low waters a day but with considerable difference between the two high waters and/or between the two low waters of the day.

It is to be noted that when the tide at any place is classed with a particular type in accordance with the above definitions, it is the generally prevailing or predominating features that are considered. For example, in figure 23 the tide at Miami would be designated as the semidaily type, although for a few days each fortnight, morning and afternoon tides exhibit some inequality. In the same way the tide at Cedar Keys would be classed with the mixed tides, although as the last 2 days of figure 23 show, but little inequality was featured by the tide. Pensacola would be classed with the daily tide because for the greater part of the time but one high and one low water a day occur.

For general purposes, the definitions of the three types of tide given above are sufficient, but it is clear that these definitions do not provide sharp distinctions between the three types. For technical purposes, definite criteria may be determined through the use of harmonic constants.

Of the five principal harmonic constituents listed in table 1, K_1 and O_1 represent the principal daily components, while M_2 and S_2 represent the principal semidaily components. The ratio of K_1+O_1 to M_2+S_2 at any place therefore defines the relative magnitudes of the principal daily and semidaily components at that place. Van der Stok (1897) suggested the use of these ratios for classifying types of tides. Where $(K_1+O_1)\div(M_2+S_2)$ is less than 0.25 the tide is classed as semidaily; where it is between 0.25 and 1.50 it is classed as the mixed type; and where it is greater than 1.50 it is classed with the daily type.

The diurnal type of tide under the above classification is found to cover a great variety of tides, from those only infrequently diurnal to those predominantly diurnal. In recent years it has been suggested (Courtier 1938) that the diurnal type be separated into two types: (1) mixed diurnal, where the ratio is between 1.5 and 3; (2) diurnal, where the ratio is greater than 3. The term "mixed diurnal," in turn, suggests mixed semidiurnal as a better designation than mixed.

For convenience, the four types of tide and the corresponding ratios of K_1+O_1 to M_2+S_2 are given in tabular form in table 2. It should be noted that the terms semidaily and semidiurnal are used as synonymous and likewise the terms daily and diurnal.

TABLE 2.—*Types of tide*

Designation	$(K_1+O_1)\div(M_2+S_2)$
Semidiurnal or semidaily	0–0.25
Mixed semidiurnal or mixed semidaily	0.25–1.50
Mixed diurnal or mixed daily	1.50–3.00
Diurnal or daily	3.00

The harmonic constants of the tide at any place are derived from tide observations at that place by means of the harmonic analysis. For a precise determination of these constants, a year of observations is desirable, but shorter series of observations will furnish dependable results. The harmonic analysis is a highly specialized process, which need not be considered here. For a detailed discussion see Manual of Harmonic Analysis and Predictions of Tides, by Paul Schureman (1940). It will be sufficient for our purposes to indicate the use of these constants in determining types of tide and in deriving tidal characteristics. Table 3 gives the four principal harmonic constants at the tide stations in the Gulf of Mexico where they have been determined. The amplitude of component N_2 throughout the Gulf is small, generally less than 0.1 foot, and is therefore not included in the table.

TABLE 3.—*Harmonic constants, Gulf of Mexico*

Station	Lat. North		Long. West		K_1		O_1		M_2		S_2		$\frac{K_1+O_1}{M_2+S_2}$	Observations	
					Amp.	G	Amp.	G	Amp.	G	Amp.	G		Year	Length
FLORIDA	°	′	°	′	*Feet*	*Deg.*	*Feet*	*Deg.*	*Feet*	*Deg.*	*Feet*	*Deg.*			
Key West (north shore)	24	34	81	48	0.28	361	0.29	357	0.55	77	0.17	101	0.79	1914	1 year.
Key West (west shore)	24	33	81	48	.29	358	.29	354	.56	71	.17	93	.79	1939	Do.
Garden Key	24	38	82	52	.37	358	.36	354	.48	84	.12	97	1.22	1860	Do.
Everglades, Barron River	25	51	81	23	.30	74	.26	67	.78	239	.22	265	0.56	1929	Do.
Naples	26	8	81	48	.50	11	.44	4	.89	143	.30	157	.79	1933–34	Do.
South Boca Grande	26	43	82	15	.41	28	.37	20	.37	150	.13	156	1.56	1933–34	Do.
Anna Maria	27	32	82	44	.48	23	.47	12	.51	134	.20	146	1.34	1933–34	Do.
St. Petersburg	27	46	82	38	.52	50	.50	40	.55	201	.19	218	1.38	1925–26	Do.
Aripeka	28	27	82	40	.53	48	.51	38	.88	191	.32	226	0.87	1933–34	Do.
Cedar Keys	29	8	83	2	.55	39	.47	29	1.07	190	.38	216	.70	1939	Do.
St. Marks Light	30	4	84	11	.56	37	.52	30	1.04	205	.43	231	.73	1933–34	Do.
Warrington	30	21	87	16	.41	47	.41	37	0.06	132	.03	130	9.11	1859	Do.
Pensacola	30	24	87	13	.44	56	.42	47	.07	173	.02	179	9.56	1939	Do.
ALABAMA															
Mobile Point Light	30	14	88	1	.38	46	.37	36	.07	117	.03	129	7.50	1850–51	Do.
Mobile	30	41	88	2	.47	80	.46	68	.05	212	.04	254	10.33	1934	Do.
MISSISSIPPI															
Biloxi	30	24	88	51	.57	48	.51	38	.11	189	.09	209	5.40	1882	Do.
Cat Island	30	14	89	10	.52	54	.48	44	.12	189	.07	202	5.26	1848	Do.
LOUISIANA															
New Orleans, Lake Pontchartrain	30	1	90	7	.09	199	.09	190	.01	60	.01	120	9.00	1898	58 days.
Pass Manchac Light, Lake Pontchartrain	30	18	90	18	.07	197	.08	199	.00	......	.01	106	15.00	1897	105 days.
New Orleans, Mississippi River	29	55	90	4	.25	101	.26	89	.02	239	.02	256	12.75	1940–41	221 days.
Port Eads, Mississippi River	29	1	89	10	.39	20	.39	11	.06	118	.04	113	7.80	1940–41	Do.
Bayou Rigaud	29	16	89	58	.32	47	.32	40	.04	169	.02	338	10.67	1948–49	1 year.
Weeks Bay	29	48	91	50	.32	105	.30	92	.16	9	.05	348	2.95	1906	Do.
Eugene Island	29	22	91	23	.56	33	.46	29	.30	253	.12	252	2.43	1941	Do.
Calcasieu Light	29	47	93	21	.46	25	.42	14	.52	259	.18	254	1.26	1933–34	Do.
TEXAS															
South Jetty Light	29	20	94	42	.49	33	.49	24	.45	276	.15	272	1.63	1936–37	Do.
Fort Point	29	20	94	46	.39	50	.36	44	.31	297	.09	301	1.88	1903–04	Do.
Galveston, Galveston Bay	29	19	94	48	.38	51	.36	42	.31	301	.10	302	1.80	1939	Do.
Gilchrist, East Bay	29	31	94	30	.26	105	.27	101	.20	37	.07	35	1.96	1936–37	Do.
Round Point, Trinity Bay	29	45	94	42	.22	134	.25	119	.13	72	.02	56	3.13	1936–37	Do.
Morgans Point	29	41	94	59	.24	139	.25	123	.09	88	.03	79	4.08	1936–37	Do.
Carancahua Reef, West Bay	29	13	95	0	.25	99	.26	88	.14	27	.04	26	2.83	1936–37	Do.
Rockport	28	1	97	3	.06	103	.06	91	.02	329	.00	......	6.00	1938	Do.
Port Isabel	26	4	97	13	.35	44	.35	35	.17	280	.04	292	3.33	1946	Do.
MEXICO															
Tampico	22	15	97	51	.43	24	.43	21	.23	250	.07	257	2.87	1942–43	Do.
Veracruz	19	12	96	8	.54	18	.63	56	.20	267	.07	187	4.33	1857	87 days.
Coatzacoalcos	18	9	94	25	.45	25	.45	19	.25	244	.07	246	2.81	1946–47	1 year.
Campeche	19	50	90	32	.87	44	.60	30	.72	271	.22	298	1.56	1900	105 days.
Progreso	21	17	89	40	.58	30	.56	21	.20	271	.06	280	4.38	1946–47	1 year.
CUBA															
Habana	23	9	82	20	.31	9	.33	5	.42	46	.14	70	1.14	1947	Do.

It will be recalled that two characteristics define or determine a given component tide, namely, the amplitude and phase or the epoch as the latter is generally called with reference to tides. Formerly, it was customary to refer the epoch to the local meridian and to designate it by the Greek letter "kappa." However, in comparing phases at different places it is more convenient to use a single meridian for reference, and the meridian of Greenwich is used for this purpose, the phase being designated by G. In table 3 the phases are all referred to the meridian of Greenwich. The stations in the table are listed in order beginning at the eastern end of the northern shore of the Gulf and continuing around the periphery counterclockwise. For several of the stations listed harmonic constants are available for several series of observations in different years. In such cases, the results from the latest year are given in the table.

For comparison with the tides in the Gulf it will be of interest to have the ratio of K_1+O_1 to M_2+S_2 for Miami Beach, on the Atlantic coast of Florida, for which place the tide curve is shown in figure 23. For Miami Beach this ratio is 0.17, and by the criteria of table 2 the tide there is of the semidaily type. From the last column of table 3 it is seen that at no place in the Gulf does this ratio fall below 0.5 so that in the Gulf the semidaily type is not represented.

From Key West to St. Marks Light the ratio is seen to be greater than 0.25 but less than 1.50 except for South Boca Grande. Hence, the tide in this stretch is of the mixed semidaily type. From Warrington to Bayou Rigaud the ratio is greater than 3, and therefore in this stretch the tide is of the daily type. From Weeks Bay around the remainder of the periphery of the Gulf to Habana the ratio fluctuates between 1.5 and 6 except for Calcasieu Light where it is 1.26 and for Habana where it is 1.14 so that the tide in this stretch varies from mixed diurnal to diurnal with only few exceptions.

The classification of the tide into types is of great convenience in tidal investigation, for as soon as the tide at any place is particularized as to type we are in possession of guiding principles for the discussion of the tide at that place. It will therefore be of advantage to summarize briefly the characteristic features of the different types of tide.

SEMIDAILY TYPE

The distinguishing feature of the semidaily type of tide is the occurrence of two high waters and two low waters in the tidal day (which has an average length of $24^h\ 50^m$) with relatively little difference between corresponding morning and afternoon tides. High waters succeed each other at intervals of about 12½ hours, and likewise the low waters.

The predominant change in range in the semidaily type of tide is that in response to the moon's phase, the greatest range, the so-called spring tides coming near the times of new and full moon, and the least range, the neap tides coming near the times of the moon's first and third quarters. The average interval between spring and neap tide is one-quarter the length of the month of the moon's phase (the synodic month), or approximately 7½ days. During this interval from springs to neaps the range of tide in the semidaily type of tide decreases from about 20 percent above the average to about 20 percent below the average; and in the next period from neaps to springs returns to 20 percent above the average or mean range.

Another prominent variation in the range of tide of the semidaily type is that in response to the moon's parallax which has a period averaging approximately 27½ days (the anomalistic month). Near the times of the moon's perigee the range of tide of the semidaily type is about 20 percent greater than average, while near the times of the moon's apogee the range is about 20 percent less than average. Obviously, therefore, at such times when the moon's perigee occurs near the times of new or full moon, the range of tide will be about 40 percent above the mean range, while at the times when the moon's apogee occurs near the times of the moon's quadratures the range will be about 40 percent less than the mean.

The third variation in range to which tides are subject is that in response to the moon's declination, which manifests itself in a difference between morning and afternoon tides, but is relatively small in the semidaily type of tide. In the moon's fortnightly change from maximum northerly to maximum southerly declination, the differences between morning and afternoon tides are greatest near the times of maximum declination and least about the times the moon is over the equator.

The range of tide is also subject to a slow change over a period of 18.6 years due to changes in the inclination of the moon's orbit to the equator. When the inclination of the orbit to the equator is at a maximum the semidiurnal range is less and when the inclination is at a minimum the semidiurnal range is greater than the 18.6 year-average. The change varies from about 3 percent below to 3 percent above average. The year 1950 corresponds to the year of minimum range, the year of the next maximum of this variation being 1959.

DAILY TYPE

The daily type of tide is characterized by the occurrence of only one high water and one low water the greater part of the time. The change from day to day in time of tide of this type is not nearly so regular as in the semidaily type in which the tide becomes later each day by about 50 minutes. In the daily type the average retardation in time likewise is 50 minutes, but from one day to the next it may vary from this average by several hours either way. This seeming irregularity in time is not due to chance effects, the tides of the daily type can be predicted quite accurately, but to the interaction of the component tides.

The most prominent variation in range of tide in the daily type is the fortnightly change associated with the moon's declination. When the moon is near its maximum semimonthly declination the range of tide in the daily type is greatest, the tides then being called tropic tides, and when the moon is over or close to the equator the tide has its least range, the tides then being called equatorial tides. This is exemplified for the tide at Pensacola by the lower curve of figure 23. For the latter part of June 1948 the moon was at its maximum southern declination on the 21st and over the equator on the 29th.

In general, it may be expected that in the diurnal type of tide, there will be several days around the time the moon is over the equator when two high waters and two low waters will occur, the larger the ratio of K_1+O_1 to M_2+S_2 the smaller the number of these days. These secondary tides pose troublesome questions in connection with the determination of the mean range of tide in tides of the diurnal type. Such secondary tides do not enter suddenly nor do they fade out suddenly. Practically, it becomes difficult to determine on a tide record whether the fluctuations are true secondary tides or fluctuations due to wind and weather. Furthermore, there is the question at what stage of development of these secondary tides shall they be included; when the range is 0.01 foot, 0.1 foot, or what?

To obviate these difficulties, it is customary to consider the diurnal tide as if it were diurnal at all times and in deriving the mean range to disregard the secondary tides. Thus, in figure 23 in the tide curve for Pensacola on the 29th, the secondary low water immediately after noon and the following secondary high water would be disregarded, and but one high water and one low water in the day would be considered. In determining mean high water and mean low water in tides of the diurnal type only one high water and one low water a day, likewise, are considered.

In figure 23, on June 23 when the moon was 2 days past its semimonthly maximum declination, the range of tide at Pensacola was 1.7 feet; on the 21st, the range was 1.9 feet. On the 29th, when the moon was over the equator the range (leaving the secondary tides out of consideration) was 0.5 foot. In the 8-day period, therefore, the range decreased 74 percent. This relatively large percentage change in range in response to the moon's declination is typical of daily tides.

At times, the terms "spring tides" and "neap tides" are used in connection with the fortnightly variation in range in the daily type discussed above, but this usage is confusing, the correct terms being tropic tides and equatorial tides. In the daily type of tide the variation in range with the moon's phases is so small that it may be disregarded for most purposes. The same remark applies to the variation in response to the moon's parallax, that is, apogean and perigean tides.

A variation in range of tide that is prominent in the daily type but not in the semidaily is of an annual period in response to the annual variation in the declination of the sun. This is illustrated in figure 30 by the results of the observations at

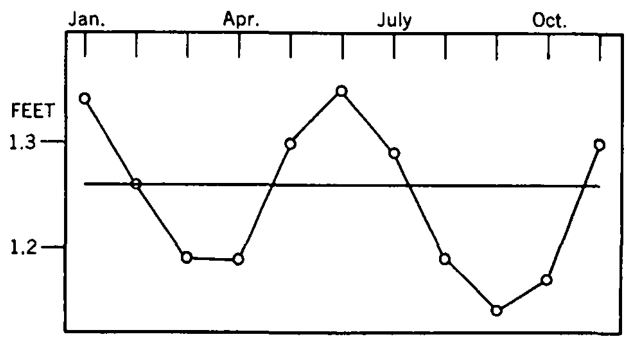

FIGURE 30.—Annual variation in range of tide, Pensacola.

Pensacola from the 19-year series 1931–49. The horizontal line, corresponding to the value of 1.26 feet, represents the mean value of the range at Pensacola, while the circles represent the average ranges for the different months of the year. During the year, the range is least in March and September, corresponding with the sun's equinox and greatest in June and December, corresponding to the sun's solstices, the difference between September and December being on the average 0.26 foot for Pensacola.

The range of tide in the daily type also is subject to a slow change of 18.6 years, due to changes in the inclination of the moon's orbit to the equator, as is the semidaily type, but is opposite in phase. During the years when the inclination of the orbit to the equator is greatest, the range in the semidaily type is less than the average, but in the daily type it is greater than the average, and during the years when the inclination is least, the range in the semidaily type is greater than the average while in the daily type it is less than the average. The results from 19 years of observations are shown in figure 31 for Miami Beach and Pensacola, illustrating the differences in the semidaily and daily types as regards this 19-year variation.

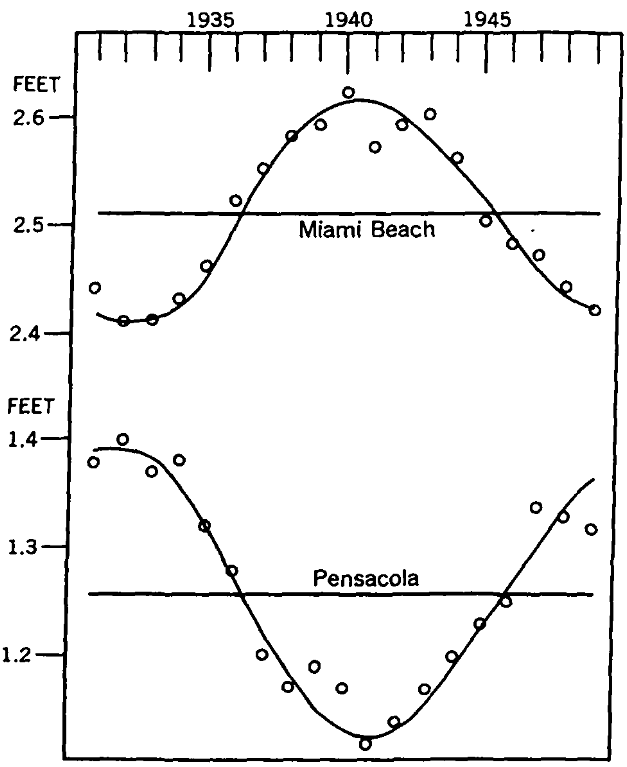

FIGURE 31.—Variation in yearly range of tide, Miami Beach and Pensacola.

The circles in figure 31 represent the yearly values of the range of the tide as derived from the continuous observations at the two stations, the more or less smooth curves being drawn to follow the yearly values with due consideration to the years of maxima and minima which are fixed from theoretical considerations. The deviations of the yearly values from the curves may be regarded as irregularities due to wind and weather.

For Miami, the change in range from the minimum in 1931–32 to the maximum in 1941 is 0.20 foot or 0.1 foot each way from the mean range which represents a change of 4 percent from the mean value of the range of 2.51 feet. For Pensacola, the change in range from the minimum to the maximum yearly value is 0.27 foot or 0.135 foot each way from the mean range which represents a change of 11 percent either way from the mean value of the range of 1.26 feet. In the daily type, therefore, the percentage change in the yearly range of tide is greater than in the semidaily type.

MIXED TYPES

From the preceding discussion of the semidaily and daily types it is clear that the mixed types of tide will vary in characteristics depending on the ratios of the semidaily and daily constituents. In the mixed semidaily type the diurnal inequality becomes a salient feature necessitating the differentiation between higher high water and lower high water and between higher low water and lower low water. The diurnal inequality, that is, the difference between the two high waters and the two low waters of a day will be greatest near the times of the moon's semimonthly maximum declinations and least when the moon is close to the equator. During the 19-year cycle there may be periods, in the years of maximum inclination of the moon's orbit, when the tide will become diurnal.

In the mixed daily tides there will be more days of the occurrence of two high waters and two low waters each fortnight near the times of the moon's crossing of the equator in the years of minimum inclination of the moon's orbit.

The changes from day to day in the features of the tide of the mixed types of tide are thus much more varied than in either of the simpler types. However, the tide tables permit the delineation of these changes from day to day. If the tide tables give the daily predictions for the place where this information is desired, the information is immediately available. Otherwise, it is necessary to infer the predictions from the predictions at some port with similar tides.

CHARACTERISTICS FROM HARMONIC CONSTANTS

From the harmonic constants formulae may be developed not only for determining the type of tide but also various characteristics of the tide. For precise results the formulae are rather involved and require other of the harmonic constants than those listed in table 3. For general purposes, however, simplified formulae are convenient for determining such characteristics approximately.

In the semidaily type of tide M_2 and S_2 are the principal components. Spring tides come when they conspire, and neap tides, when they are opposed. Hence, the formula 2.0 (M_2+S_2) gives an approximate value of the spring range, and 2.0 (M_2-S_2) gives an approximate value of the neap range. The mean range is given approximately by $2.2M_2$.

In the daily type of tide K_1 and O_1 are the principal constituents. When K_1 and O_1 conspire, tropic tides occur, and the formula for the tropic range, 2.0 (K_1+O_1), gives an approximation to the tropic range. The mean range for a daily type will be given approximately by 1.5 (K_1+O_1).

In the mixed types of tide things are more complicated, but the formulae for the ranges of the semidaily type may be used for the mixed semidaily, and the formulae for the daily tides may be used for the mixed diurnal.

In the discussion of the combination of component tides (p. 106), it was found that the phase relations between the daily and semidaily components determined whether the inequality would be featured principally in the high or low waters or equally in both. The following rule applies: If the difference between $M_2°$ and $(K_1°+O_1°)$ is zero, the inequality is wholly in the high waters; if the difference is 90°, the inequality is exhibited in equal degrees in both high and low waters; if the difference is 180°, the inequality is wholly in the low waters. In the application of this rule, the difference between $M_2°$ and $(K_1°+O_1°)$ is taken without reference to the sign of the result, and when this difference is greater than 180°, it is to be subtracted from 360°.

To exemplify the use of this rule, we may apply it to the harmonic constants in table 3 for Key West, Cedar Keys, Galveston, and Habana. From table 3, the values of $M_2°-(K_1°+O_1°)$ are, disregarding the sign of the result: Key West, 641°, or after subtracting from 2 × 360° gives 79°; Cedar Keys, 122°; Galveston 152°; Habana 32°. In accordance with the above rule, Key West with a value of 79° should exhibit inequality in both the high and low waters with the high water inequality somewhat the higher; Cedar Keys, with 122° should likewise exhibit inequality in both the high and low waters but with the greater inequality in the low waters; Galveston, with 152° should exhibit the inequality principally in the low waters; Habana, with 21° should have its inequality principally in the high waters. Looking back to figures 23, 24, and 26, it is found that the tide curves at these places conform to the findings from the harmonic constants.

In the discussion of the different types of tide, spring tides were defined as those coming "near the times of new and full moon" and tropic tides were defined as those coming "when the moon is near its maximum semimonthly declination." This somewhat indefinite phraseology is necessary because between any astronomical occurrence and the resulting maximum effect upon the tide there is usually a lag. In the spring or neap tides this lag is known as the phase age, and for the tropic or equatorial tides it is known as the diurnal age. These ages vary from place to place but can very readily be computed from the harmonic constants. In hours, the phase age is given by the formula 0.98 $(S_2°-M_2°)$ and the diurnal age by 0.91 $(K_1°-O_1°)$. Thus, from table 3 we find that at Key West, spring tides come 0.98 (101−77) =23.5 hours, or a day after full or new moon; and at Pensacola, tropic tides come 0.91 (56−47)= 8 hours, or a third of a day after the moon's maximum semimonthly declination.

The harmonic constants lend themselves to the derivation of various other features of the tides, but the necessary formulae and calculations are rather involved and would be out of place here. The interested reader is referred to U. S. Coast and Geodetic Survey Sp. Pub. 260, Manual of Harmonic Constant Reductions.

DISTURBING EFFECTS OF WIND AND WEATHER

The regularity in the periodic rise and fall of the tide and in its cyclic variation is subject to the disturbing effects of changing meteorological conditions. These disturbances arise primarily from the changes in the level of the water brought about by the changing meteorological conditions. In changing the level of the water from which the tide rises and falls wind and weather disturb both the times of occurrence and the heights of the high and low waters.

With respect to the disturbances brought about by changes in barometric pressure the water in any coastal body of water may be regarded as constituting a huge water barometer. When the barometric pressure over this body of water rises as compared with the pressure over the open sea the water inside will fall, while with a lesser pressure the water will rise. Since the specific gravity of mercury is about 13 times that of water a change in barometric pressure of 1 inch should be accompanied by a change in the level of the water of a little more than a foot.

Actually, however, the matter is not quite so simple, for it is not so much a question of difference in barometric pressure over a coastal body of water and the open sea as it is of barometric gradient. Furthermore, pressure differences are accompanied by winds, and the effects of the latter on the rise and fall of the tide are much more pronounced than the direct effects of barometric pressure.

From general considerations, it is clear that in waters having equal ranges of tide the same wind will have greater disturbing effects in the body of water having the lesser depth. Likewise, in bodies of water of equal depth, a given wind will be accompanied by greater disturbing effects in the body of water having the lesser range. Finally, in waters having equal depths and ranges of tide, wind effects are more disturbing on tides of the mixed and daily types than on tides of the semidaily type, and since in the Gulf the depths are relatively shallow, the ranges of tide rather small and the type of tide mixed and diurnal, it is to be expected that the disturbing effect of the wind on the tide will be quite pronounced.

For any particular stretch of coast, too, the hydrographic features enter as factors into the effects of a given wind. The problem is therefore a complex one necessitating detailed studies for each body of water. Such studies are almost completely wanting. In connection with notable storms, the heights attained by high water will be noted by the meteorologist or engineer studying the effects of the storm in a particular harbor.[1]

Needed, too, are studies correlating to the height of the tide at various places to storm tracks so that approximately accurate predictions of the height of a storm tide to be expected may be made from the characteristics of a developing meteorological disturbance. A closely related problem, the use of observed changes in the tide to furnish information regarding the direction and movement of a storm still far out in the Gulf, is discussed by Cline (1920).

In bays and harbors receiving the flow from large drainage areas the tides are also subject to disturbances arising from variations in run-off. In general, however, these disturbing effects become pronounced only in the upper reaches of tidal streams.

THE TIDE IN THE GULF OF MEXICO

Thus far, the discussion of the tides at various places in the Gulf of Mexico has considered the tide at each place as a local phenomenon. How do these tides tie together? In other words, what is the dynamics of the tidal movement in the Gulf as a whole? What explains the relatively large diurnal component in the Gulf as compared with the Atlantic Ocean? Only few investigations of this character have appeared in print.

S. F. Grace (1932) briefly reviews the explanations offered by various investigators. The dynamics of the tide in any large body of water is a difficult problem. In the Gulf of Mexico, it is further complicated by the irregular shape of the basin and by its connections with the Atlantic Ocean and the Caribbean Sea which pose the question of co-oscillation with the tidal movements in those bodies of water.

Qualitatively, the simplest explanation of the relatively large diurnal component in the Gulf is that the length and depth of its basin are such that its free period of oscillation approximates 24 hours; that is, it approximates the period of the diurnal tide-producing forces and therefore responds better to the diurnal forces than to the semidiurnal forces.

[1] See for example: The Galveston Hurricane of September 8, 1900, Monthly Weather Review, Sept. 1900, pp. 371-377, and The Tidal Storm at Corpus Christi and Its Effect on Engineering Structures, Engineering News-Record, Nov. 13-20, 1919, pp. 848-852.

In the above-mentioned article, Grace studied the K_1 component and constructed a cotidal chart for that component from which "the motion appears to be that of a wave entering through Florida Channel, progressing round the basin in the positive sense, suffering reflexion at the northwesterly and southerly coasts, and leaving by Yucatan Channel; the time occupied by this progression is about six hours."

SEA LEVEL

The term "sea level" is used to designate the level or elevation of the sea from which the tide rises and falls. In other words, it is the level of the sea freed from the rise and fall of the tide and is derived by averaging the hourly heights of the tide for a period of one or more days. It is convenient, too, to use the expressions daily sea level, monthly sea level, and yearly sea level to denote, respectively, the sea level derived by averaging the hourly heights of the tide for the period of a day, month, or year.

If the hourly heights of the tide at any place are averaged for each day over a number of days, it is found that sea level fluctuates from day to day by amounts varying from less than a tenth of a foot to more than a foot. During a single month sea level on one day may differ by several feet from that on another day. These relatively large fluctuations are obviously to be ascribed to the effects of wind and weather which vary from day to day.

If now we derive sea level for a month, we find that from one month to another sea level may fluctuate by as much as half a foot, and within a year, two monthly values of sea level may differ by a foot. Since the seasonal change in wind and weather is largely periodic, the question arises whether the change in monthly sea level likewise is periodic. On investigation, this is found to be the case, and in figure 32 are shown the average heights of monthly sea level at nine tide stations in the Gulf of Mexico based on three or more years of observations.

It is customary to explain the annual variation in sea level as due primarily to the effects of wind and weather, but studies giving quantitative relationships in the Gulf of Mexico between the annual variation in sea level on the one hand and wind and weather on the other hand are wanting. In general, it is seen that throughout the Gulf sea level is low in the first half of the year and high in the autumn. It is of interest to note, too, on the United States coast, the marked increase in the secondary minimum in the summer at the stations west of the Mississippi River.

The curves of annual variation for Coatzacoalcos, Progreso, and Habana must be considered as approximate only, being based on a few years of observations.

In connection with the determination of mean sea level at any place, it is clear that in view of the seasonal variation in sea level, a month of observations can give only an approximate value. Within a year, however, the seasonal variation is eliminated, and the fluctuations due to the disturbing effects of wind and weather tend to balance out. In figure 33 are shown the yearly values of sea level at the four stations for which 20 years or more of observations are available.

Disregarding for the moment the dashed-line curve associated with each of the diagrams, it is seen that sea level from one year to another may differ by amounts varying from several hundredths of a foot to several tenths of a foot. The larger fluctuations must obviously be ascribed to the disturbing effects of wind and weather which do not repeat themselves exactly from year to year. These fluctuations can be eliminated by smoothing by moving means, and a more or less smooth curve derived. In that manner, the dashed-line curve for each of the yearly sea level diagrams was derived.

For Key West, there appears to have been little change in sea level from 1913 to 1930, after which there appears to be a more or less regular rise amounting to 0.37 foot by 1950, or a little less than 0.02 foot per year. In this connection, it is of interest to note that the change in sea level at this station approximates the change found at the tide stations along the Atlantic coast of the United States from Florida to Massachusetts (Marmer 1949).

At Cedar Keys the break in the observations from 1925 to 1938 allows only tentative conclusions, but the evidence is for little change in sea level between 1915 and 1925 and a gradual rise from 1939 to 1950 of about 0.3 foot. This gives a rise at the rate of a little over 0.02 foot per year

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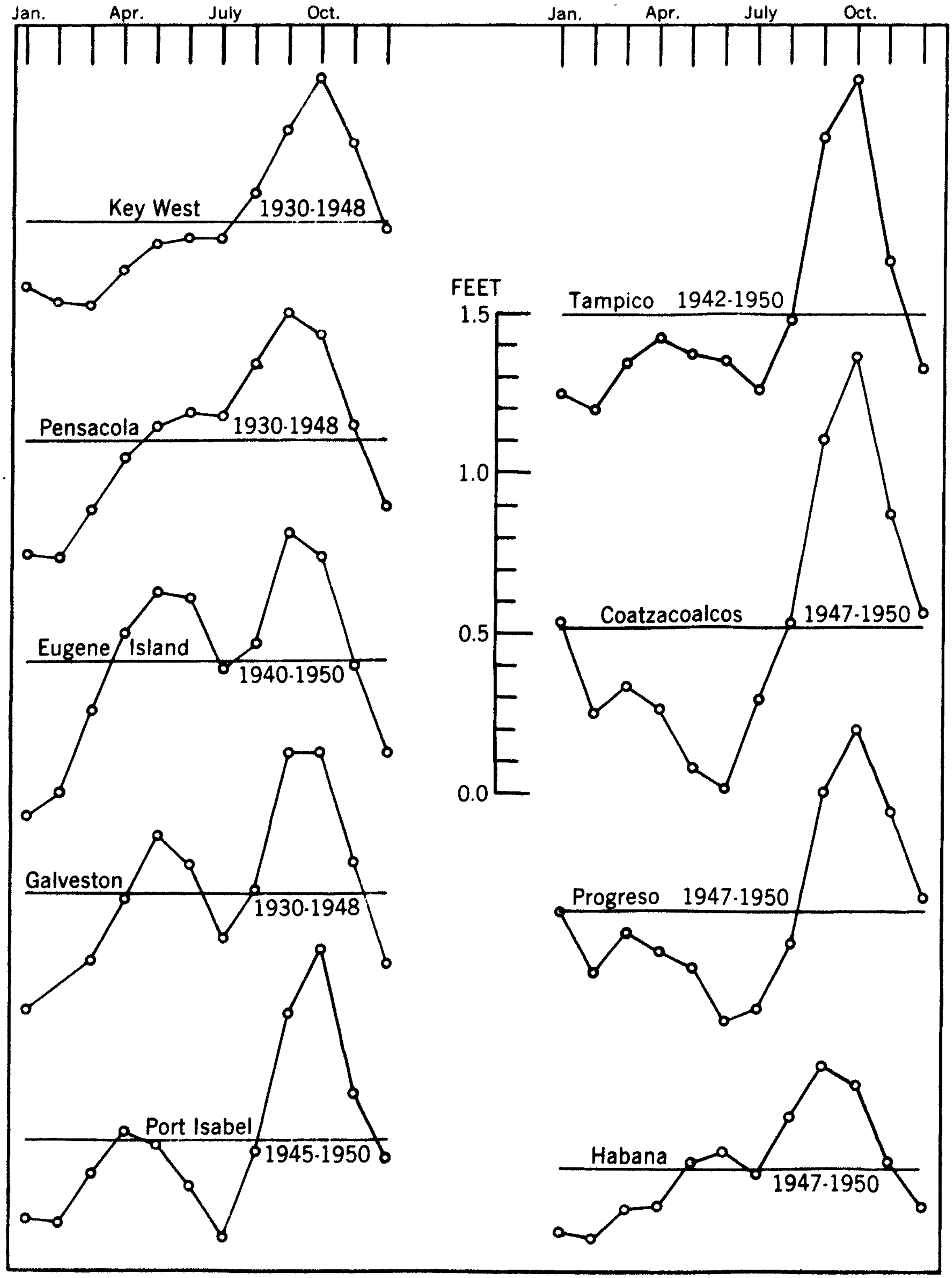

FIGURE 32.—Annual variation in sea level at nine tide stations, Gulf of Mexico.

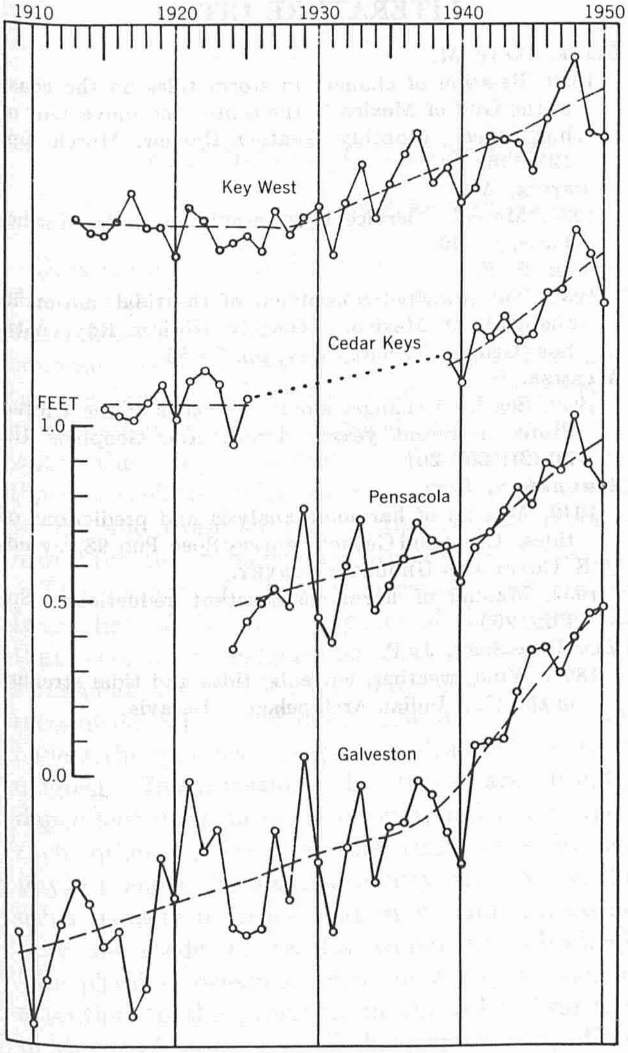

FIGURE 33.—Yearly sea level, Key West, Cedar Keys, Pensacola, and Galveston.

for the past 11 years, or at a rate somewhat larger than at Key West.

At Pensacola, the rise in sea level from 1924 to 1950 is very nearly half a foot. From 1924 to 1941 the rise was at the rate of about 0.01 foot per year, but since then the rate appears to be a little over 0.03 foot per year.

At Galveston, the change in sea level from 1909 to 1950 is almost exactly 1 foot. From the diagram of figure 33, sea level appears to have risen more or less uniformly from 1909 to 1937 about 0.4 foot or at the rate of 0.014 foot per year. From 1938 to 1950 sea level rose 0.6 foot or at the rate of 0.05 foot per year or at a rate more than three times that of the earlier period.

For the northern shores of the Gulf the observations available indicate a rise of sea level in recent years but at different rates at the different places. Furthermore, in the last decade or two the rise has been at a more rapid rate at all four stations of figure 33. These matters clearly pose questions of a geophysical nature which fall outside the restricted field of tides.

It is of interest to note, however, that a change of sea level at a given place may be due to one or more of several different causes. Clearly, if a coastal area is subsiding, sea level in that area will rise relative to the coast, but a rise in sea level will also occur along a stable coast if the volume of the water in the open sea has increased. It appears likely that such an increase, at a very slow rate to be sure, is taking place at the present time through an amelioration of the climate in high latitudes, testified to by the recession of glaciers, the melting waters of which are finding their way to the open sea. Long-continued deposition in the sea of river-borne material from the land tends to decrease the depths of the sea and thus cause a rise of sea level. Finally, even with stability of the coast, of the volume of water in the sea, and of the depths of the sea, a rise in sea level at a particular place may conceivably occur through a change in the seasonal distribution of the direction and velocity of the winds.

AVAILABILITY OF TIDAL DATA

Tidal data for the Gulf of Mexico are available in various forms. Tide Tables, East Coast, North and South America, issued annually in advance, give daily predictions for a calendar year of the heights and times of high and low water for Key West, Tampa Bay, St. Mark's River entrance, Pensacola, Mobile, Galveston, and Tampico Harbor. In addition, these tables list Tidal Differences and Constants for many other places in the Gulf which permit approximate predictions to be made by reference to the above standard stations.

The Coast and Geodetic Survey also issues, in looseleaf form, descriptions and elevations of the tidal bench marks it has established in various places along the United States coast of the Gulf. These describe the location of each bench mark and its elevation above mean low water. For each locality there is given, in addition, a table listing the highest and lowest tides observed or inferred, and the heights of mean high water, half tide level, and mean low water.

At the present time, there are in operation by the Coast and Geodetic Survey 10 primary tide stations located as follows: in Florida, at Key West, St. Petersburg, Cedar Keys, and Pensacola; in Louisiana, at New Orleans, Bayou Rigaud, and Eugene Island; in Texas, at Galveston, Rockport, and Port Isabel. Most of these stations have been in operation for a number of years, at Galveston, for example, since 1909. For each of these stations there are available, in the files of the Coast and Geodetic Survey at Washington, tabulations giving the hourly heights of the tide and the times and heights of high and low waters. There are also available summaries giving the monthly and yearly heights of high water, low water, and sea level.

Tide stations have also been operated in recent years by the governments of Mexico and Cuba.

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PHYSICAL OCEANOGRAPHY OF THE GULF OF MEXICO [1]

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Oceanography may be defined as the study of the oceans in all their aspects, including the interrelationships between the seas and their boundaries—the atmosphere, the shoreline, and the sea bottom. Physical oceanography consists of the analysis of the physical properties of sea water, the study of motions in the oceans such as those associated with ocean waves, tides, and winds, and examinations of the various mechanisms for the transfer and interchange of energy.

The nature of physical oceanography differs from that of the other aspects of the subject in that certain investigations may be conducted somewhat independently. The other generally recognized aspects of oceanography are the biological, the chemical, the geological, and the meteorological. Investigations in these are usually dependent upon physical oceanography and upon each other. It is desirable that work in the physical aspect be planned jointly with that in the other aspects in order that maximum utilization may be made of results which are obtained. The physical oceanographer must pay particular attention to the problems in the other branches of the work since one of the primary objectives of his own researches is the development of information needed for the solution of some of these problems.

There are many unique opportunities in the study of physical oceanography in the Gulf of Mexico. There is an offshore oil industry facing many problems related to construction and operation in the shallow waters over the wide continental shelf, there is a huge chemical industry which has an output depending heavily upon the varying longshore currents which alter the salt content of the water at the position where it is taken into the plants, and there are many characteristic weather features such as hurricanes, squalls, and fog which result from effects of the oceans upon the atmosphere. Further, the large oyster and shrimp fisheries are markedly affected by currents, turbulence and the physical characteristics of the sea water. Also, in reduction of beach contamination, prevention of beach erosion, reduction of dredging costs in marine channels, increasing the efficiency of marine transportation, development of recreational areas on the beaches, and in providing oceanographic information critical to the defense of our coastline, physical oceanography plays a most important role in the Gulf of Mexico.

The Gulf, being nearly enclosed, provides a model ocean in which much may be learned about processes operating in the larger oceans which are not so readily adaptable to comprehensive and systematic analysis. The presence of fixed platforms far from shore may make it possible for the first time to make such determinations as that of the effect of the wind in changing the slope of the sea surface in the open sea. Such information is needed for further development of the theories of wind stress upon the sea surface and for the more complete understanding of the manner in which the winds drive the ocean currents and set up ocean waves.

Despite the need for physical information in the Gulf, relatively little has as yet been done to survey the region systematically and to provide information in a form which is generally available. Recently there have been increased efforts in this direction, and within the near future it may be expected that knowledge of this highly important oceanic region will be greatly increased.

OCEAN CURRENTS

The primary problem in the physical oceanography of any region is the determination of the ocean currents. In the Gulf of Mexico it is particularly difficult. To provide a background for a discussion of this problem it is well to consider

[1] Contribution from the Department of Oceanography of the Agricultural and Mechanical College of Texas, Oceanographic Series No. 16; based in part on investigations conducted for the Texas A. and M. Research Foundation, through the sponsorship of the U. S. Navy Office of Naval Research.

briefly the general nature of the currents which may be expected in such a region.

The general nature of currents in the Gulf of Mexico

Sverdrup (1942) [2] lists three different groups of currents each of which is represented in the Gulf of Mexico. These are:

(1) currents that are related to the distribution of density in the sea,

(2) currents that are caused directly by the stress that the wind exerts on the sea surface, and

(3) tidal currents and currents associated with internal waves.

Tidal currents [3] are caused by the tide-producing forces. These forces result from differences between the constant centrifugal force which acts on any particle on the earth and the varying gravitational attractions between the earth, the moon, and the sun. These attractions are proportional to the masses of the bodies and inversely proportional to the squares of the distances between them. Because of its very short distance from the earth the attraction of the moon is large. The sun, on the other hand, although it is at a much greater distance from the earth, is so large that a tide-producing force results which is as much as 46 percent of that of the moon.

The direct result of tide-producing forces acting upon the rotating earth is to raise and lower periodically the level of the ocean's surface, i. e., to create tides. Water which is required to raise sea level at a particular location must be furnished by horizontal movements within the ocean. These are the tidal currents. Since the sun and moon change their position with respect to a given part of the earth's surface in a periodic fashion, the tides and tidal currents are periodic. Because the rotation of the earth affects movements of water the tidal currents do not oscillate back and forth on a straight line but rotate. In the Northern Hemisphere this rotation usually is in a clockwise direction except where modified by other factors. At times, interference between tidal waves or the influence of other forces is such that the rotation may be counterclockwise.

Along the Gulf coast there are many bays and lagoons which have relatively restricted outlets to the sea. If the water level in these bays is to be raised by tidal action, all of the water required for the change in level must flow into the bay through these restricted channels. Therefore, the tidal currents in such channels may be quite large, particularly at certain stages of the tide.

The great width of the shallow continental shelf along the Gulf coast results in tidal current velocities which are relatively high considering the small range of tide. This is because the change of water level of this large area over the shelf must be brought about by flow across the shallow shelf. Since the depth of the moving water is small, its velocity must be relatively great to provide the volume needed for change in sea level. The high velocities and the changing direction and speed of these tidal currents may lead to considerable turbulence and stirring in certain localities.

Oscillating currents related to internal waves may be important in this region, but little information now is available on this subject.

Currents caused by the stress of the wind upon the sea surface are particularly important on the Gulf coast. The most widely known phenomenon which results from the action of such currents is the storm tide or general rise in water level which precedes winds of hurricane velocities. Storm tides are discussed by Cline (1920) and Tannehill (1927). Some of their results are summarized in the chapter on meteorological phenomena.

When a wind starts to blow over the ocean it exerts a frictional force or drag upon the sea surface. If the wind persists the surface layers of the water start to move and they in turn act upon the deeper layers and set these in motion also. The two forces which are involved in setting up such currents are the frictional force, and the Coriolis force which is the apparent force due to the rotation of the earth. If the wind blows long enough for a state of equilibrium to be reached, the surface waters away from the influence of the coast will be moving in a direction approximately 45° to the right of the wind direction in the Northern Hemisphere. A north wind sets up a surface current toward the southwest. The surface velocities may reach 1 to 2 percent of the wind velocity. Currents at greater depths will flow at greater angles to the wind and at speeds which decrease with depth.

[2] References are listed at the end of the chapter.

[3] Tides in the Gulf of Mexico are discussed separately in the article by H. A. Marmer, pp. 101-118.

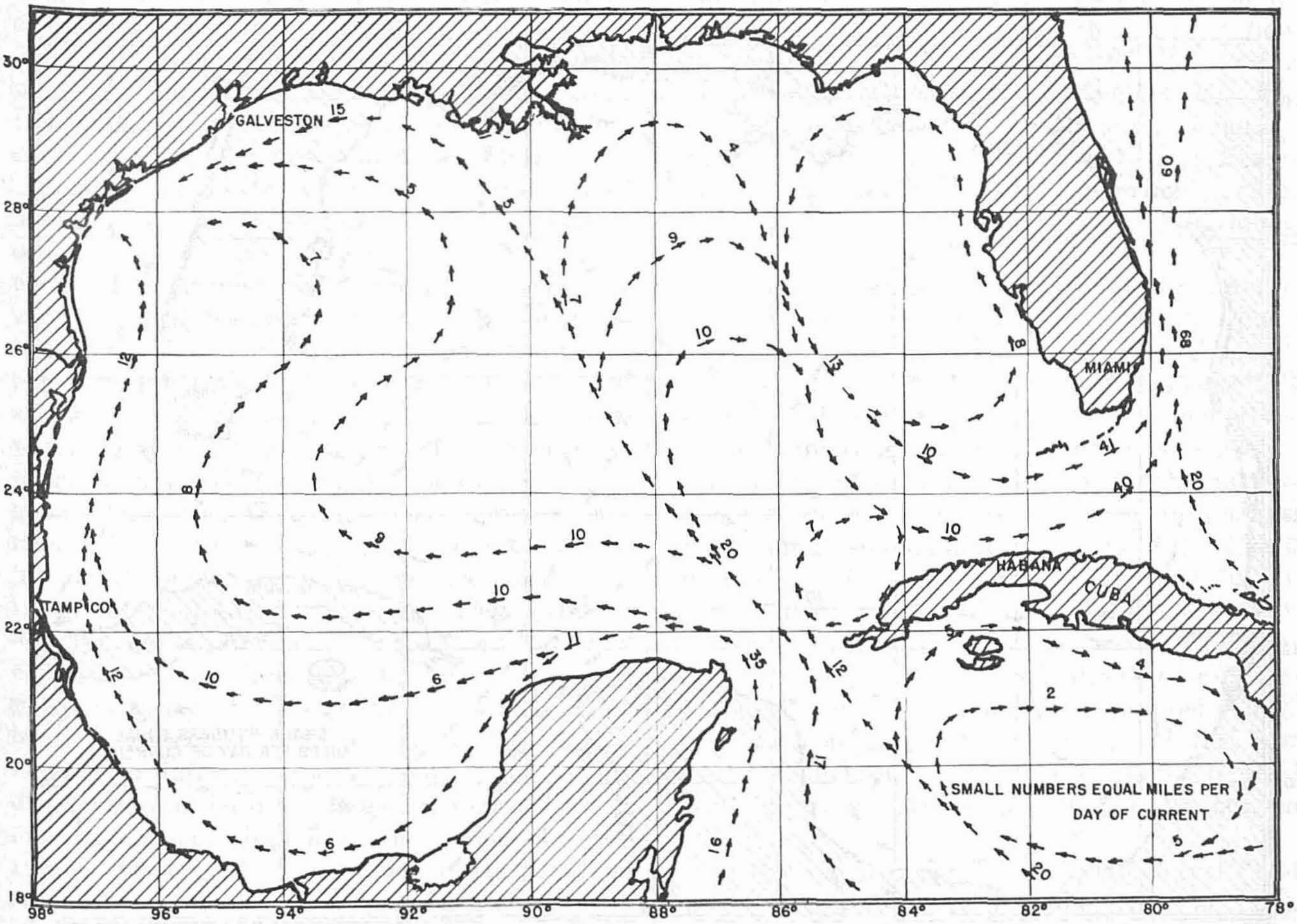

FIGURE 34.—Surface ocean currents in the Gulf of Mexico in June.

Conclusions concerning currents set up by the wind are mostly based upon theoretical considerations. A few observations have been made in landlocked bays to show the piling up of water by the wind. However, in the open ocean no systematic data are available. The drilling platforms off the Gulf coast permit the accumulation of data which will make possible a practical analysis.

The currents related to the distribution of density are the major semipermanent currents of the oceans. Little is known about these currents in the Gulf of Mexico. The chief source of information is the pilot charts of the United States Navy Hydrographic Office (figs. 34 and 35). These are based upon the navigation records of the ships sailing in the Gulf over many years. They do indicate the general drift in various regions, but the individual observations upon which they are based are subject to many errors. For example, the deviation of a ship from its course may be caused by the wind rather than by the current. Also, it is difficult to determine positions at sea accurately. A survey of the pilot charts for the Gulf indicates that these may not describe all of the currents present. They show waters flowing into the western part of the area at all latitudes but no water flowing out. This situation cannot exist unless there is a submarine return current of equal magnitude, which seems unlikely.

In the deep waters, direct observation of current velocities has been almost impossible until recently because of difficulty in anchoring vessels. Accordingly, few such observations have been made. Instead, oceanographers have developed a method based upon principles of physics. By use of this method the ocean currents present may be inferred from the distribution of density as determined by relatively simple observations of temperature, salinity, and pressure. Two forces again

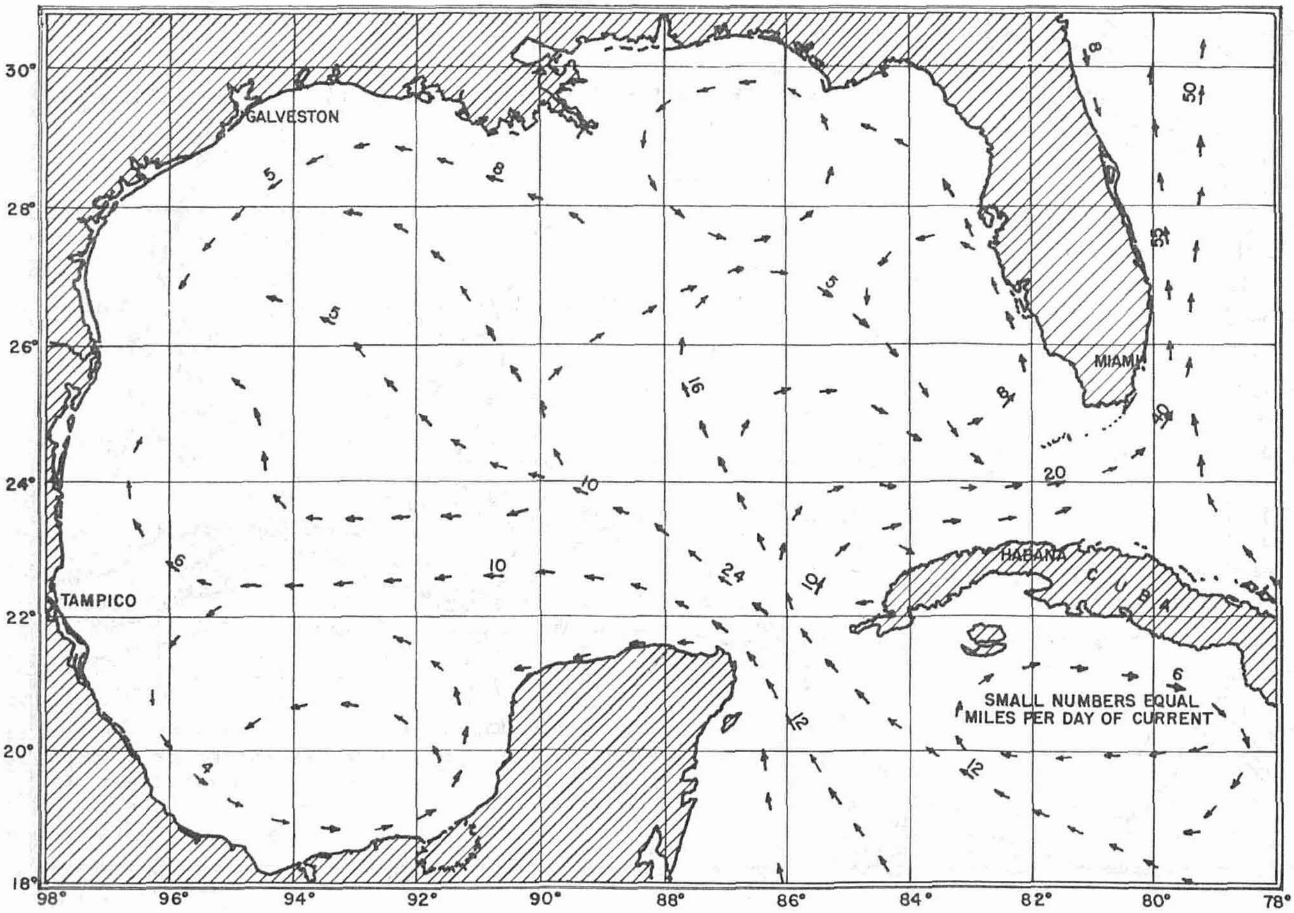

FIGURE 35.—Surface ocean currents in the Gulf of Mexico in December.

are involved, one of these being the Coriolis force and the other the "pressure force" which is a force that depends upon the water density distribution in the earth's gravitational field. The pressure force tends to make water flow from a region of high pressure toward a region of low pressure just as water poured into less dense oil will flow outward from the point at which it is poured. When the movement related to the pressure gradient has begun, the Coriolis force acts toward the right of the movement in the Northern Hemisphere and the resulting equilibrium between the two forces is associated with a steady current flowing almost perpendicular to a line connecting the regions of high pressure and low pressure. This flow is such that in the Northern Hemisphere the more dense water is on the left of a person standing with his back to the current and the less dense water is on his right. Since temperature is one of the major factors influencing density, it may be inferred that the cold water is on the observer's left and the warm is on his right when he is standing as described above with relation to the current. Thus, he can tell something about the currents if he knows the distribution of temperature, or he can tell something about the temperature if he knows the distribution of currents.

There are a number of difficulties which arise in applying the current computation method. These occur partly because the basic assumptions underlying the theory are not always fulfilled. However, despite these difficulties the method has been found to be the one which provides the most information for a reasonable amount of work. It is not known how accurately the Gulf currents in deep water may be determined by this method, but there is reason to believe it to be the most accurate of the methods now in use. Used in conjunction with the geomagnetic electrokinetograph, it probably provides the best complete picture of the current patterns in the open Gulf. Determination of the flow over the broad, shallow continental shelf remains a difficult problem.

Some processes by which the distribution of density is caused to change are evaporation, conduction, and the movement of masses of water by the winds. Since the total transport of water due to the winds in this hemisphere is toward the right of the wind, and since this transport consists of waters in the surface layers which are warm and of low density, the low density waters are piled up at the right of the wind flow, which is in the center of anticyclones, regions of good clear weather. The warm waters are removed from the low pressure storm areas at the left by the wind action. These movements are called the wind-driven currents. Their primary effect is to pile up water of small density in areas of anticyclonic winds and to leave waters of greater density in areas of cyclonic winds. This leads to a secondary effect, namely, the maintenance of a different ocean current related to this distribution of density. Since such currents flow nearly perpendicular to a line connecting the regions having the different water densities, the associated currents form a pattern quite similar to the pattern of the winds. This may readily be recognized on charts showing the distribution of ocean currents with prevailing winds superimposed.

Investigations of ocean currents in the Gulf of Mexico

There is probably no part of the oceans of the world of comparable size to the Gulf of Mexico where there is such a wide difference of opinion concerning the specific current regime. This difference is brought out by Sweitzer (1898). He quotes Isaac Vassius who, writing about the year 1663, tells how the currents through the Yucatán Channel "turn obliquely" and pass through the Straits of Florida. The issue of the Encyclopedia Britannica available in 1898 states that "a portion of it (the current—DFL) passes directly to the northeast along the shore of Cuba; but by far the larger part sweeps around the Gulf." Sweitzer himself concludes that, at times "the channel of Yucatán pours its waters into the Gulf so that they spread out in all directions moving on its center," while at other times the currents flow "in a northeasterly direction around the extreme west coast of Cuba." These last results were based upon studies of the distribution of specific gravity of the surface waters, United States Coast and Geodetic Survey, Lindenkohl (1896), and upon modification of currents by the prevailing winds.

Sweitzer also reported considerable agitation of the waters covering an area of about 100 square miles occurring off the coast of Texas about 40 miles south and 20 miles east of Aransas Pass which could only be accounted for by the meeting of two opposing currents. Other evidence of converging currents has since been found, and this area has become known as the graveyard of ships.

Measurements made in the years 1885 to 1889 by the United States Coast and Geodetic Survey vessel *Blake*, commanded by Pillsbury (1889), determined the currents in the Straits of Florida. Since the ship was anchored, direct current observations could be compared to computed values, and the comparison provided one of the best examples illustrating the validity of the method for computing relative currents which is now so widely used.

Agassiz (1888) published temperature and salinity data collected by the *Blake* in 1878. These data, together with others collected by the *Bache*, Bigelow (1917), were used by Wüst to compute the transport of the water through the Florida Straits as 26 million m^3/second. Associated with this transport is a water level difference of 19 cm. between the southeastern Gulf and the Atlantic at St. Augustine, Florida, which is discussed by Montgomery (1938). A theory of piling up water in the "Bay of Mexico" was advocated by Benjamin Franklin about 1770.

In 1922, the *Dana* made some observations in the Yucatán Channel and in the Florida Straits, as shown in figure 36. These observations, as well as those of the *Mabel Taylor* in 1932, were summarized by Parr (1935) who concluded that "evidence thus obtained from the Gulf itself, although directly opposed to some of his premises, nevertheless serves to confirm the theory already advanced by Nielsen on the basis of observations in the Straits alone, that the so-called Gulf Stream only takes the shortest possible path from its entrance through the Yucatán Channel to its

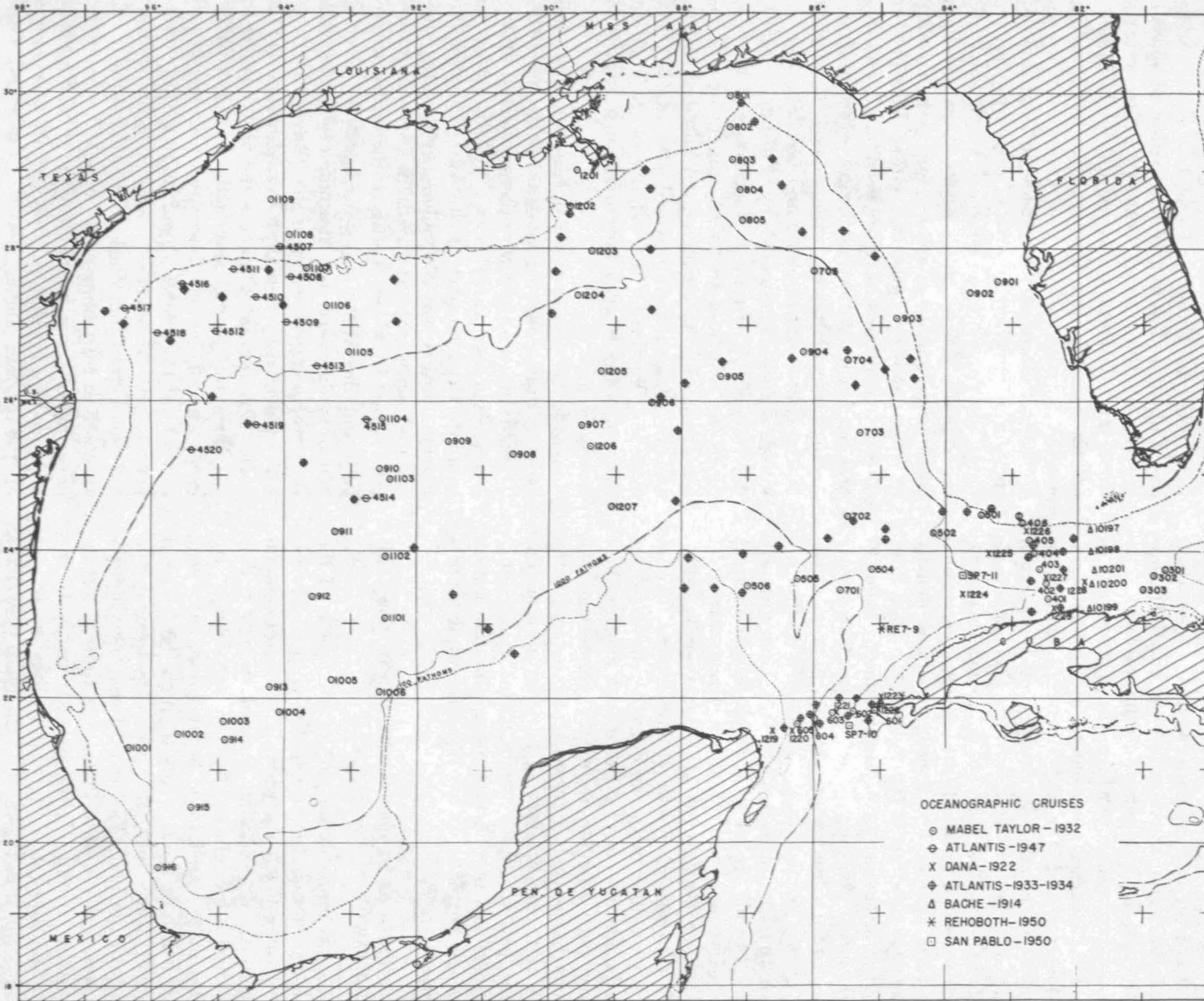

FIGURE 36.—Hydrographic stations in Gulf of Mexico.

exit through the Straits of Florida, without deviating on the way, or diffusing any to itself significant amount into the Gulf of Mexico proper, or receiving any predominant contribution from the Gulf in return." This statement on the one hand and the current pattern shown in figures 34 and 35 on the other hand summarize the present divergence of opinion.

The *Mabel Taylor* cruise was made without unprotected thermometers or other reliable means of determining depth of observations. Parr cautions that particularly in the Yucatán Channel and Florida Straits there is sufficient uncertainty of the depths of the *Mabel Taylor* operations "to make it seem inadvisable to subject them to a form of analysis and comparison in which depth is an essential consideration." Similarly, the *Atlantis* cruise of 1934, Parr (1937), lacks subsurface data since the hydrographic cable was lost early in the survey. Thus, the oceanographic data available to Parr were meager.

Dietrich (1939) reviewed the currents of the Gulf, and his conclusions, although based upon essentially the same data as used by Parr, show considerably more influence by the Gulf Stream upon the general circulation in the Gulf. He discussed the sill depths showing that the Gulf circulation cannot affect the deep water circulation of the Atlantic below about 800 meters. However, the Florida current, which is shallower than this, has considerable effect.

In 1947 the *Atlantis* conducted a survey of the northwestern Gulf making 27 hydrographic stations (fig. 36) and 473 bathythermograph observations of temperature. These data have been analyzed by Fred B. Phleger (1951), now of the Scripps Institution of Oceanography of the University of California, and have been published by the Geological Society of America.

The first cruises of the *Alaska*, oceanographic research vessel of the Fish and Wildlife Service operating on a survey of the Gulf of Mexico with the cooperation of the Department of Oceanography of Texas Agricultural and Mechanical College and the United States Navy, Office of Naval Research, were completed in October 1951 (fig. 37). These provide the first complete coverage of the Gulf with information needed to compute the deep water currents. The data from these cruises have been distributed and prelimary analyses indicate that they support the main features of the current pattern shown in figure 34.

A brief description of the currents of the Gulf of Mexico is provided in the United States Coast Pilot (1949):

> Under normal conditions, at all seasons of the year, the great volume of water passing northward through Yucatán Channel into the Gulf of Mexico, spreads out in various directions. Surface flows set westward across Campeche Bank, the Gulf of Campeche, and the Sigsbee Deep; northwestward toward Galveston and Port Arthur; north-northwestward toward the Mississippi Passes; and eastward into the Straits of Florida.
>
> A straight line drawn from Buenavista Key, Western Cuba, to the Mississippi Passes forms an approximate boundary between movements having different directions. West of this line the drift is generally northward or westward, while east of it the drift is eastward or southeastward toward the Straits of Florida.
>
> There are northward flows along the west side of the Gulf between Tampico and Corpus Christi in the vicinity of the 100-fathom and 1,000-fathom curves, north of the Sigsbee Deep between the 2,000-fathom and the 100-fathom curves, and along the west coast of Florida.
>
> In general, the surface circulation is the same at all seasons. There is, however, some seasonal change in velocity, the flow being generally stronger in spring and summer than in the autumn and winter.
>
> The current near the Florida Keys is variable and uncertain.

This description is apparently taken from the Pilot Chart series of the Hydrographic Office (H. O. No. 3500, issued monthly). Another series, H. O. No. 10,690, 1 to 12, Current Charts of the Central American Waters, give resultant direction and velocity for each 1° quadrangle of latitude and longitude. This series has been used by Smith, et al. (1951), to show zones where seasonal convergence or divergence occur.

Many of the references cited above contain bibliographies pertinent to the Gulf of Mexico. Also, Geyer (1950) lists many useful works.

In summary, the currents of the Gulf of Mexico and their variations are not specifically known. Studies completed in the past indicate some unusual and interesting features and provide incentive and justification for continued intensive investigation.

SEA SURFACE TEMPERATURES

A large number of sea surface temperature observations have been collected at shore stations. Some of these data from locations shown in figure

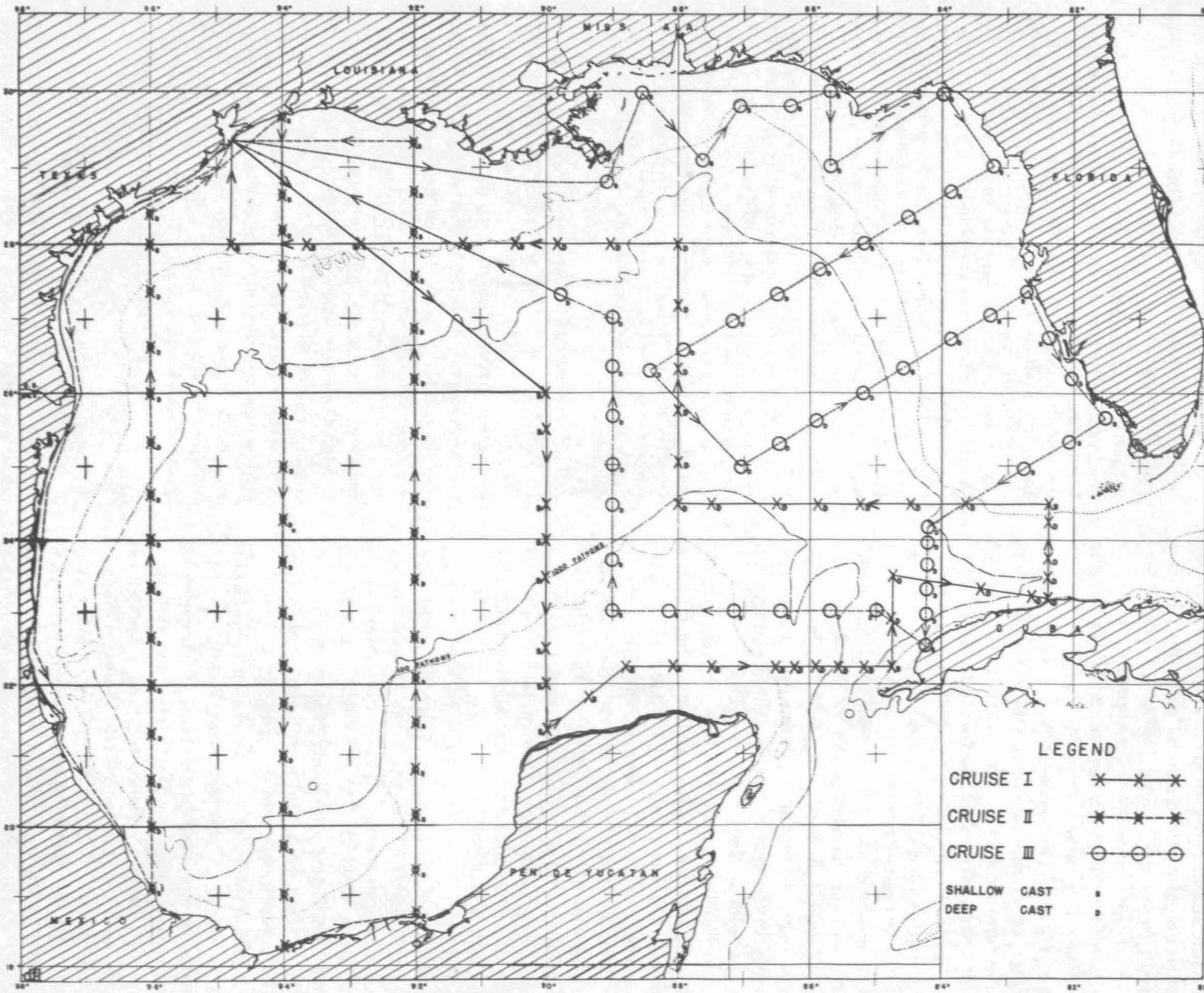

FIGURE 37.—Cruise plan for U. S. Fish and Wildlife vessel *Alaska*, September 1950.

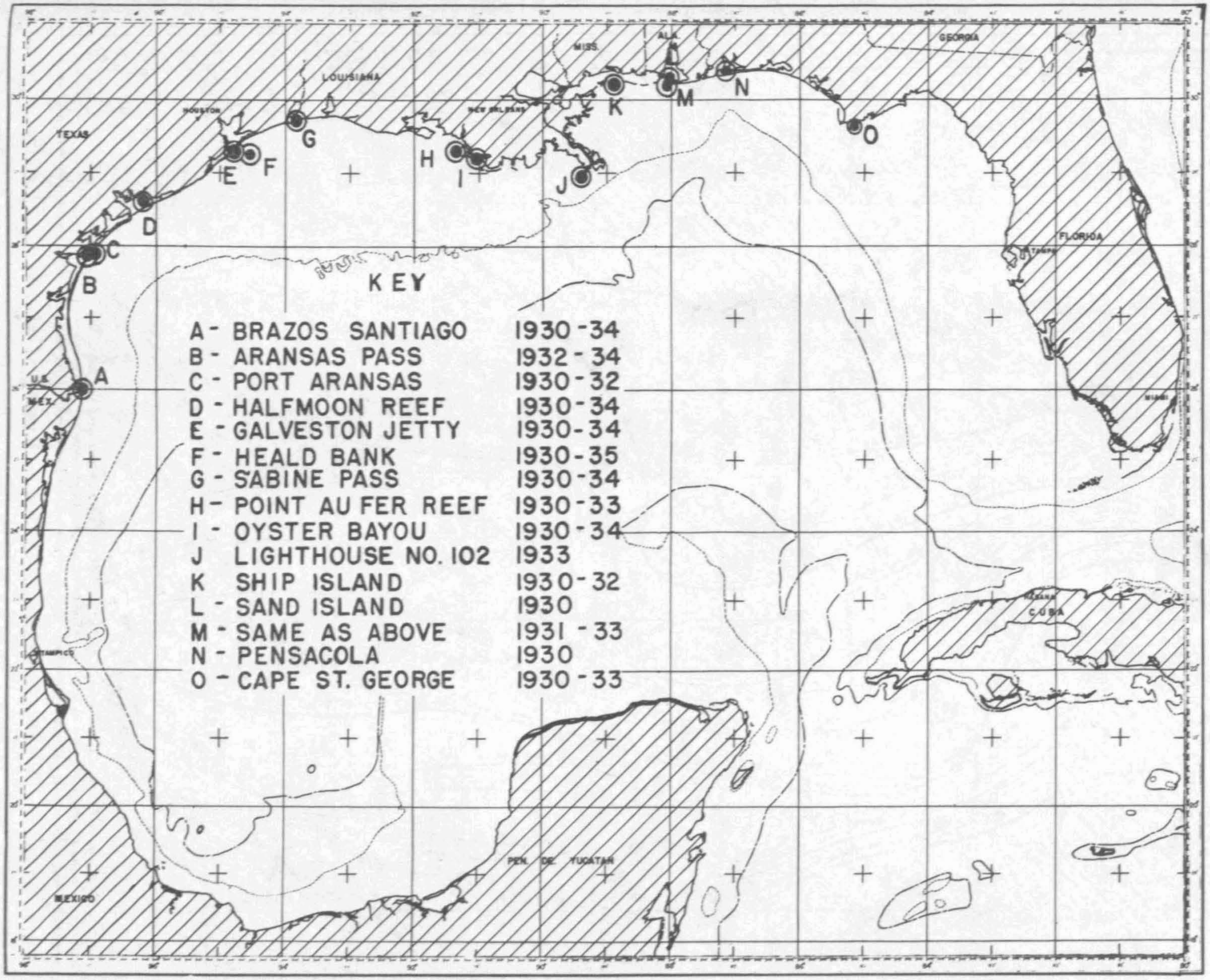

FIGURE 38.—Shore stations measuring sea surface temperature.

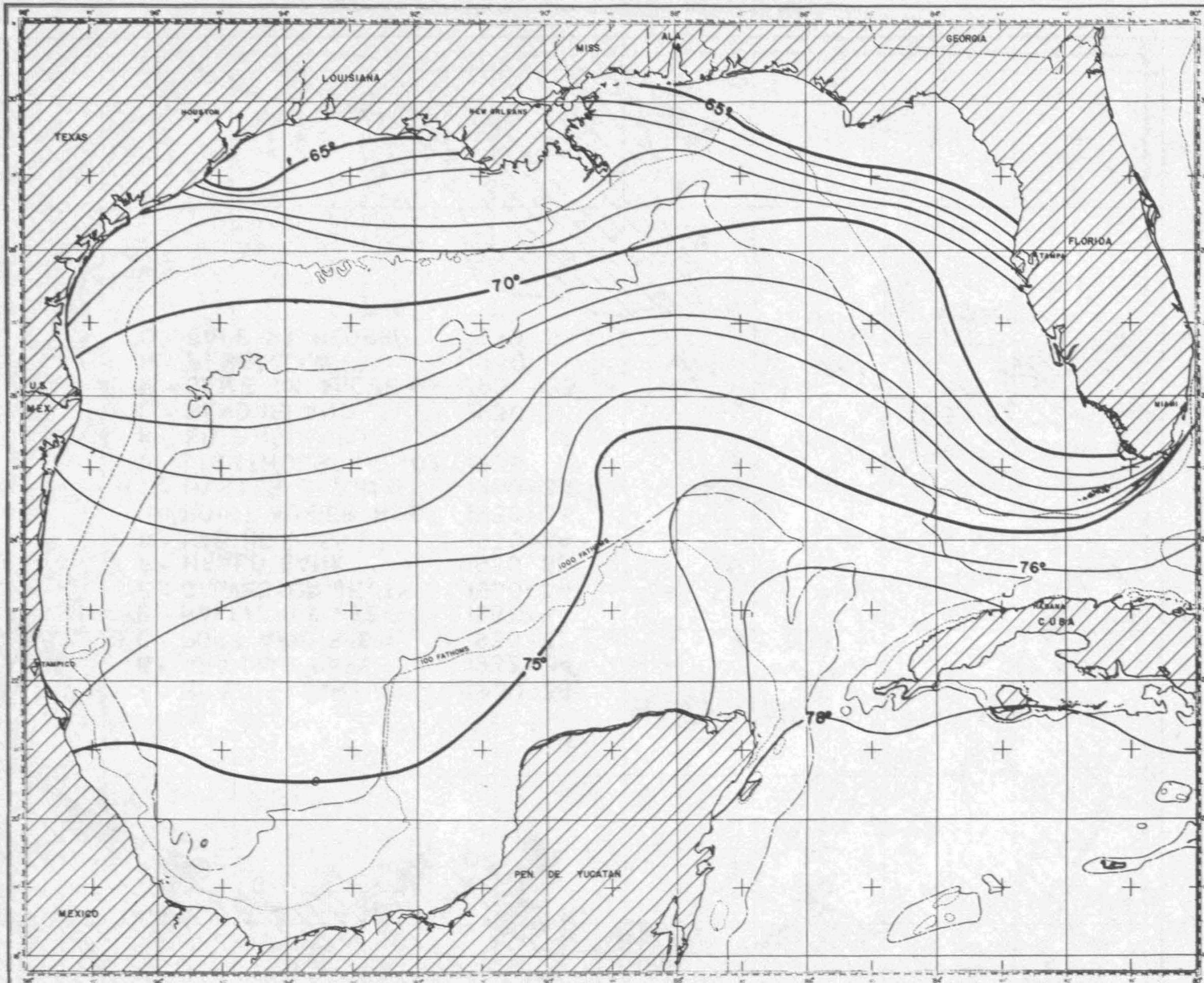

FIGURE 39.—Average sea surface temperatures for February (after Fuglister).

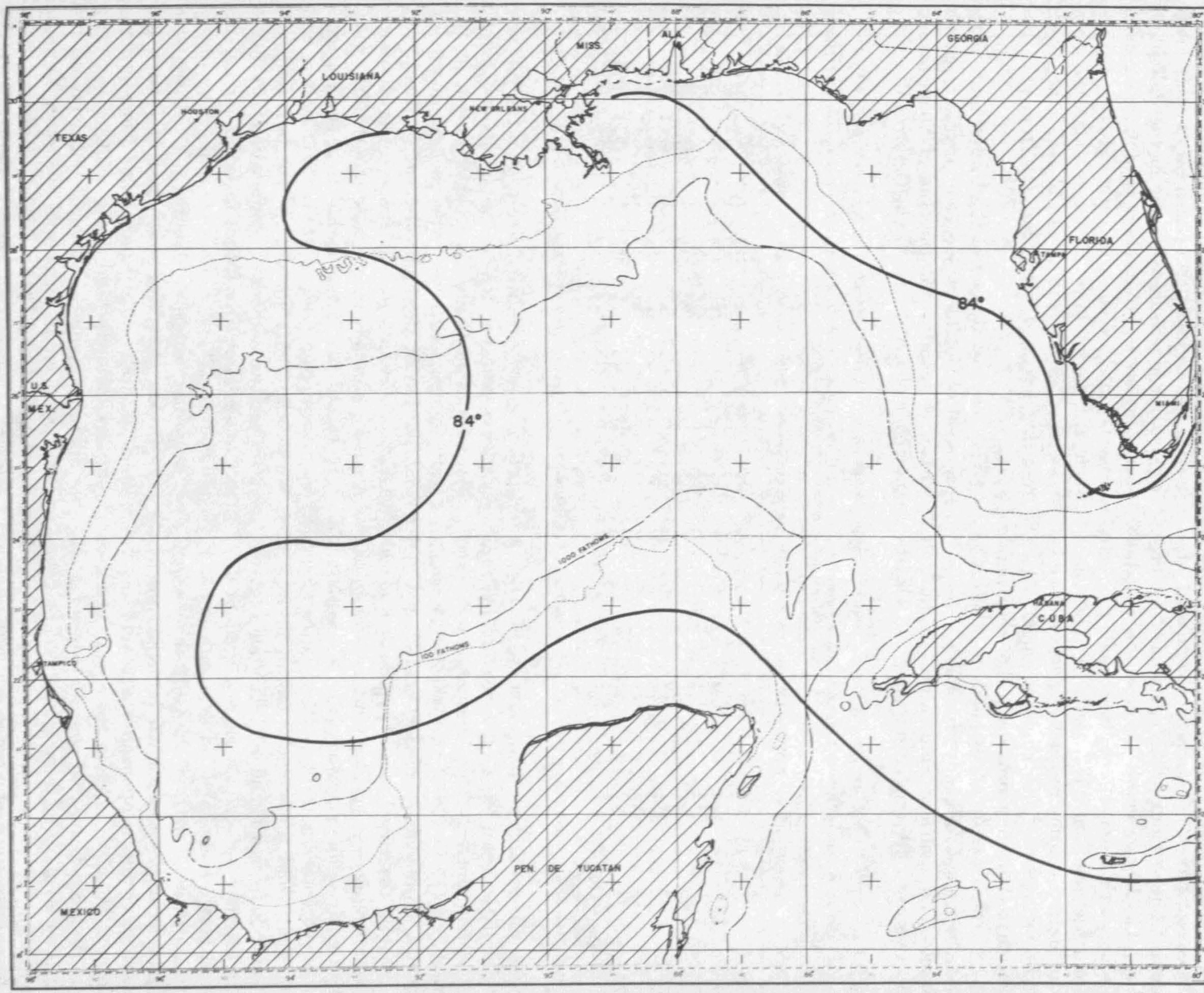

FIGURE 40.—Average sea surface temperatures for August (after Fuglister).

38 have been made available through the Fish and Wildlife Service of the United States Department of the Interior and are on file in the Department of Oceanography at Texas Agricultural and Mechanical College where a file-report has been prepared. The key in figure 38 shows the period of years in which observations were made and sent in from each station. The study of these shore station data is continuing, and references to additional information of this kind are sought. It is hoped that they may provide a clue to general changes which are occurring offshore where observations are not so readily obtainable.

Studies of sea surface temperatures in the Gulf of Mexico have been based on some 200,000 observations taken on ships in this area over a period of more than 50 years. The majority of these observations were made with the instruments carried as a regular part of each ship's equipment. Due to the possibility of error in the individual thermometers and to errors in reading, the results must be interpreted with care. However, with such a large number of observations the nonsystematic errors tend to cancel each other, with resulting averages being not far from the true mean.

The Weather Bureau of the United States Department of Commerce has computed average sea surface temperatures in the Gulf of Mexico using the above observations. Table 1 shows the average sea surface and air temperatures for the 12 months of the year, the Gulf being divided into eight 5° quadrangles. This information was taken from charts 115 to 126 of the Weather Bureau's Atlas of Climatic Charts of the Oceans.

TABLE 1.—*Monthly average sea surface and air temperatures in the Gulf of Mexico (in degrees Fahrenheit)*

[Figures in italics are averages of dry bulb thermometer readings observed as a rule on the ship's bridge. Figures in roman are mean sea surface temperatures, obtained mainly from bucket sampling]

Area	100-95W 30-25N		95-90W 30-25N		90-85W 30-25N		85-80W 30-25N		100-95W 25-20N		95-90W 25-20N		90-85W 25-20N		85-80W 25-20N	
January	*66.8*	67.7	*63.6*	67.9	*68.1*	72.5	*69.3*	73.2	*70.7*	73.0	*72.6*	74.3	*74.1*	76.3	*71.9*	75.0
February	*66.9*	68.3	*63.7*	67.3	*68.3*	72.1	*69.2*	72.7	*70.4*	72.6	*72.7*	73.9	*74.1*	76.0	*72.1*	74.7
March	*67.5*	68.8	*66.3*	68.5	*69.8*	72.6	*70.9*	73.2	*72.7*	73.3	*73.9*	74.6	*75.3*	76.4	*73.3*	75.3
April	*73.3*	72.6	*71.1*	71.6	*73.3*	74.6	*74.0*	75.2	*75.4*	75.4	*76.2*	76.1	*77.1*	77.7	*75.9*	76.8
May	*75.6*	76.3	*75.9*	76.0	*77.3*	77.7	*77.5*	77.9	*78.6*	78.5	*78.8*	78.6	*79.4*	79.5	*78.7*	79.0
June	*80.3*	80.5	*80.3*	80.6	*80.8*	81.0	*80.6*	80.8	*80.8*	81.1	*81.0*	81.2	*81.2*	81.6	*81.3*	81.5
July	*83.1*	82.6	*82.5*	83.1	*82.4*	82.9	*82.3*	82.6	*81.7*	82.5	*82.1*	82.4	*82.2*	82.6	*82.7*	83.0
August	*82.9*	83.3	*83.0*	83.9	*82.9*	83.7	*82.6*	83.4	*82.5*	83.3	*82.4*	83.2	*82.5*	83.2	*83.0*	83.8
September	*81.8*	83.3	*81.5*	82.8	*81.8*	82.9	*81.9*	82.9	*81.6*	83.1	*82.1*	83.2	*82.2*	83.1	*82.3*	83.4
October	*77.2*	80.2	*76.4*	79.4	*77.8*	80.3	*78.5*	80.7	*79.1*	81.3	*80.2*	81.6	*80.1*	81.8	*79.6*	81.5
November	*77.2*	76.3	*70.4*	74.7	*72.8*	76.7	*74.0*	77.5	*75.1*	77.9	*76.5*	78.5	*76.9*	79.5	*75.8*	78.8
December	*69.3*	70.7	*65.4*	70.7	*69.8*	74.2	*70.9*	75.0	*71.7*	74.5	*73.8*	75.9	*75.2*	77.7	*73.3*	76.5

NOTE.—From Charts 115-126, Atlas of Climatic Charts of the Oceans, U. S. Department of Commerce, Weather Bureau.

Probably the most recently prepared charts showing average sea surface temperatures in the Gulf are those of Fuglister (1947). Isotherms reproduced from his work for the winter month of February and the summer month of August are shown in figures 39 and 40. The main feature of the average winter pattern is a gradual drop from approximately 75° F. in the south to 65° F. in the north in all parts of the Gulf, the gradient being larger in the east portion. In the summertime the average temperatures are very nearly uniform at 84° F. throughout the region. Cruises of the *Alaska* indicate that considerable deviation from these average isotherms may occur at certain times.

The annual range of normal sea surface temperature varies from 15° to 20° F. in the northern portion of the Gulf, while in the central and southern portions the range is about 10° F. February is normally the coolest month of the year, though January is the coolest month for that portion of the Gulf adjacent to Texas and Mexico. Except for a few scattered areas, August is normally the warmest month of the year.

In regard to diurnal variation of surface temperature in the Gulf, a study by Stommel and Woodcock (1951) presents some data and discusses various methods of computation. It makes recommendations for future investigation of this problem.

According to Storey (Gunter 1947), there were nine freezes along the west coast of Florida between 1886 and 1936 which killed fishes in large numbers. Intense cold spells, sufficiently severe to kill large numbers of fishes, occurred along the Texas coast on an average of one every 14 years between 1856 and 1940, with less damaging spells coming at shorter intervals. Similar data for other parts of the Gulf coast are not available.

Slocum (1934–36) has made a comparative study of sea surface temperatures for various regions of the Gulf in different years. This study is based on temperature observations taken from 1912 to 1933. The year-to-year changes are summarized in table 2 for the regions shown by encircled numbers in figure 41. The mean temperature for each year has been computed. It is of interest to note that in one case the minimum mean yearly temperature for a given region for this period of years differed from the overall mean temperature for the region by 2.1° F. Moreover, the maximum and minimum mean yearly temperatures differ by 3.1° F. in two localities. For one of these extreme examples, in the region 27–29° N., 90–93° W., the lowest mean yearly temperature recorded was for the year 1915 which showed a mean temperature of 73.9° F. In 1922 and 1927, the highest mean temperatures were recorded here, being 77.0° F. For the other example, the low was 77.8° F., the high 80.9° F. Slocum's study also included consideration of the means for the different months of the year.

TABLE 2.—*Some variations of mean annual sea surface temperatures for 1912–33* [1] *in various regions of the Gulf (° F.)*

[After Slocum]

Variation	(1) 25–26° N. 84–86° W.	(2) 27–29° N. 90–93° W.	(3) 26–28° N. 86–89° W.	(4) 21–25° N. 90–94° W.	(5) 23–24° N. 82–84° W.	(6) 21–22° N., 85–87° W. 22–23° N., 84–87° W.
High	79.5	77.0	78.7	79.7	80.9	81.1
Dif	1.1	1.5	0.9	1.2	1.0	0.8
Mean	78.4	75.5	77.8	78.5	79.9	80.3
Dif	1.6	1.6	1.2	0.9	2.1	1.0
Low	76.8	73.9	76.6	77.6	77.8	79.3
High-Low Dif	2.7	3.1	2.1	2.1	3.1	1.8

[1] The number of observations varies from year to year. Few observations were made in 1917–19. In other years, the number ranged from 100 to over a thousand in each region. Locations are shown in figure 41.

SEA TEMPERATURE VARIATIONS WITH DEPTH

The sea temperatures obtained by the *Mabel Taylor* below the surface have been published by Parr (1935). Although the depths of these observations are not known accurately, they do give considerable information about vertical temperature distribution. An average temperature-salinity correlation in the Gulf of Mexico proper as worked out by Parr for the months February–April is given as table 3.

In the early 1940's the United States Navy developed the bathythermograph for making observations of sea temperature continuously from the surface to depths as great as 900 feet. To date, some 10,000 observations or bathythermograms have been made in the Gulf. Copies of these are now filed at the Woods Hole Oceanographic Institution where they are processed and in the Department of Oceanography at Texas Agricultural and Mechanical College. Their distribution by 1° quadrangles is shown in figure 42.

TABLE 3.—*An average temperature-salinity correlation for the Gulf of Mexico proper*

[After Parr]

Average temperature	Average salinity	Weighted average depth
° C.	°/₀₀	m.
24.74	36.19	5
23.06	36.06	15
21.03	36.14	58
19.25	36.28	94
17.09	36.22	125
14.85	35.95	192
13.00	35.68	237
10.89	35.35	321
9.60	35.16	380
8.57	35.04	432
7.42	34.93	562
6.39	34.88	647

Two bathythermograms, one for summer and the other for winter, were chosen from each of four parts of the Gulf within the 1,000-fathom line. These locations are indicated by encircled crosses in figure 41. The bathythermograms were chosen as being typical after considering range of temperature variation, general shape of temperature-depth curve, depth of thermocline, and other features. Unfortunately, due to the paucity of observations it was not possible at any one of the four positions to obtain "typical" summer and winter bathythermograms from the same year. However, by plotting a typical summer and a typical winter bathythermogram for each position on the same coordinates it was possible to show in a general

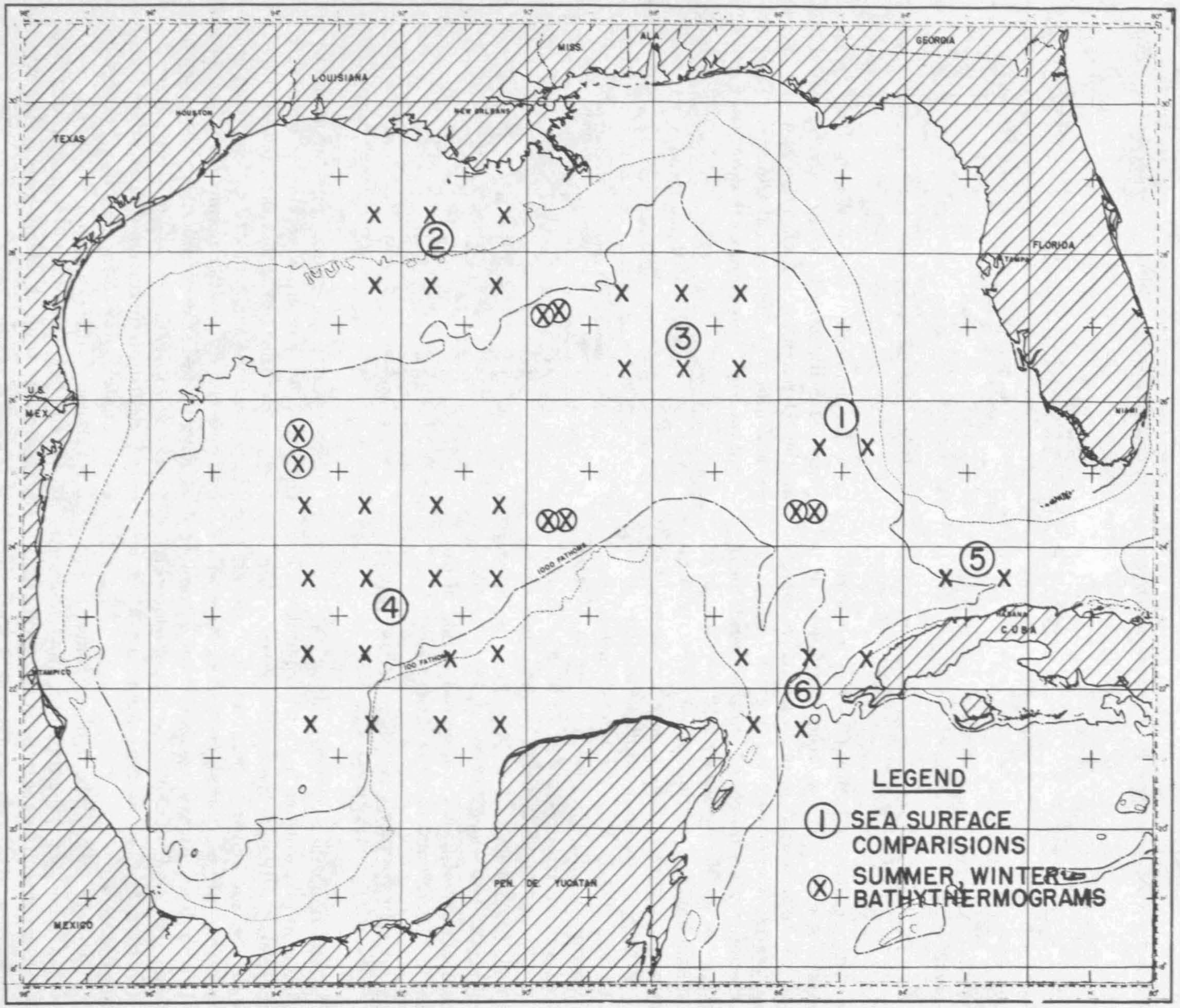

FIGURE 41.—Regions where comparative studies of sea temperatures were made.

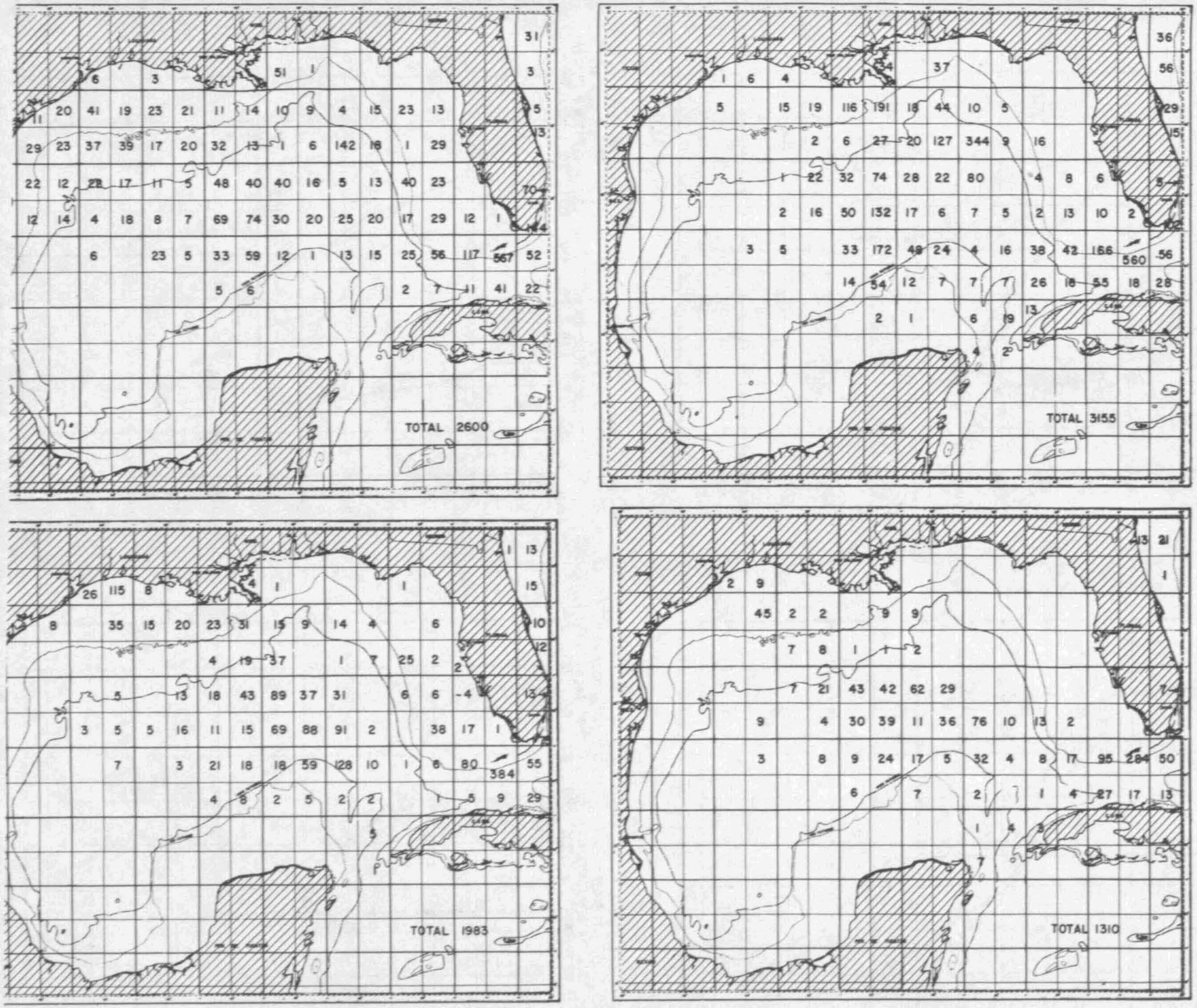

FIGURE 42.—(Upper left) Distribution of available bathythermograms January, February, March, 1941 through 1949. (Upper right) Distribution of available bathythermograms April, May, June, 1941 through 1949. (Lower left) Distribution of available bathythermograms July, August, September, 1941 through 1949. (Lower right) Distribution of available bathythermograms October, November, December, 1941 through 1949.

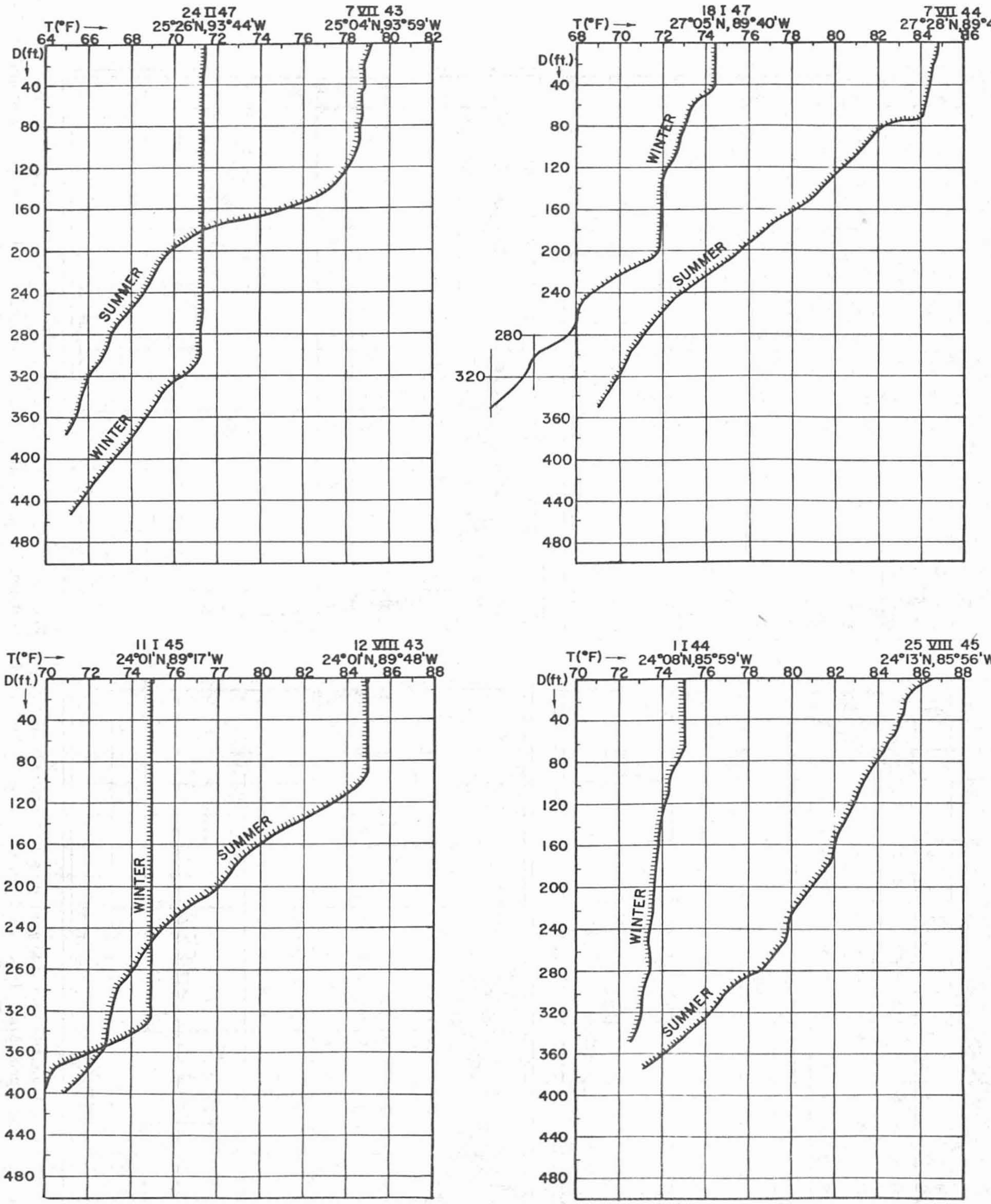

FIGURE 43.—Typical summer and winter bathythermograms from different areas in the Gulf of Mexico.

way the seasonal differences. These curves are presented in figure 43 which gives the date and position of each observation. Typical curves properly selected are believed more representative of conditions than average ones, since certain characteristic features of temperature structure may be lost in the process of averaging. A report by Adams and Sorgnit (1951) gives similar information for each 1° quadrangle of the Gulf where data were available. It also shows the contours of the bottom of the mixed or isothermal layer in summer and winter insofar as can be determined.

SALINITY

Parr (1935) presents a chart of the distribution of average salinities in the upper 50 meters of the Gulf of Mexico. It shows the values to be typically 36.00 parts per thousand over the entire central region. Water from the Mississippi River reaches to depths of 50 meters and extends beyond *Mabel Taylor* station 1106 (fig. 36), a distance of 150 miles, keeping salinities below 36.00 parts per thousand. Near stations 1201 and 1202 the river extends its influence on salinity only about 85 miles seaward.

From the Yucatán Channel a subsurface intrusion of water having salinity over 36.50 parts per thousand extends north and bends westward to the central part of the Gulf. From February to April this tongue underwent a marked shift westward in position of some 120 miles according to the *Mabel Taylor* data.

Above 50 meters waters of salinity greater than 36.25 parts per thousand are found over both the wide Campeche and Florida Banks indicating possible upwelling of the subsurface intrusion.

Average variation of salinity with depth is shown in table 3.

TEMPERATURE-SALINITY RELATIONSHIPS

An average temperature-salinity relationship for the Gulf proper was shown in table 3. A single station typical of what Parr defined as the Gulf Complex is *Mabel Taylor* station 705 (fig. 36). Another which he calls typical of the Caribbean Complex, divided from the Gulf Complex by a line extending from the northeast corner of Yucatán Bank to the southwest corner of the Florida Bank, is station 701 (fig. 36). Data for these stations are listed in table 4. The primary difference between these two distributions is that at temperatures above 18° C. the Gulf Complex station has markedly lower salinities, being below 36.32 parts per thousand, while the Caribbean station has values as high as 36.73 parts per thousand.

The T–S curves in the Yucatán Channel do not seem to vary significantly from year to year, but those in the Straits of Florida are not so stable, particularly at temperatures above 20° C. Cruises in different years in the Straits have shown wide variations in the extent of Gulf water found in the upper 200 meters.

TABLE 4.—*Typical temperature and salinity data*

[After Parr]

Gulf Complex Station 705, Feb. 18, 27°42′ N., 86°00′ W.			Caribbean Complex Station 701, Feb. 16, 23°28′ N., 85°37′ W.		
Depth	Salinity	Temperature	Depth	Salinity	Temperature
m.	‰	° C.	m.	‰	° C.
0	35.52	23.75	0	36.18	25.34
30	36.15	23.15	100	36.32	25.28
100	36.32	18.59	200	36.73	21.88
150	36.21	16.58	300	36.44	18.21
200	35.96	14.94	400	35.94	14.96
300	35.52	12.30	600	35.08	9.12
500	35.08	7.88	800	34.86	6.86
700	34.87	5.91	1,000	----------	5.15
900	34.92	4.94			
1,200	34.95	4.21			
1,500	34.97	4.21			
2,000	34.97	4.16			
2,500	34.97	4.22			
3,000	34.97	4.24			

Parr (1935) believes that since—

> The presence of Gulf waters in the Straits of Florida is . . . identified with the location in which a countercurrent running in the opposite direction of the Caribbean-Florida Current flow is usually indicated on the hydrographic charts. . . . it seems reasonable to draw the tentative conclusion "the water masses of the Gulf of Mexico proper should be considered part of the coastal water system of the North and Central American Atlantic seaboard and not as part of the oceanic-circulation system of the Caribbean and Florida Currents."

Considerable further evidence is required to fully support this tentative conclusion.

Below 800–1,200 meters depth observations of the *Mabel Taylor* showed hydrographic conditions in the Gulf so extremely uniform that it was not considered advisable to attempt to prepare vertical profiles for the deep layers. More accurate depth determinations on subsequent investigations may bring out significant variations at these depths.

OCEAN WIND WAVES AND SWELL

A basic and easily obtainable reference for climatic data on waves in the Gulf is the Atlas of Sea and Swell Charts of the United States Navy Hydrographic Office (1943-50), Miscellaneous Publication No. 10,712, A through D. Certain uses of these data are discussed by Fleming and Bates (1951).

Information concerning wave heights in some regions on certain specific days may be obtained by referring to wind data available through the United States Weather Bureau and applying a method of calculation described in United States Navy Hydrographic Office Publication No. 604, Techniques for Forecasting Wind Waves and Swell.

The problem of wave action on structures is discussed by Munk (1947). Considerable additional research will be required before knowledge of wave forces in the Gulf is complete. Such work has been underway at the University of California (La Jolla and Berkeley) and is being initiated at Texas Agricultural and Mechanical College.

SHALLOW WATER OCEANOGRAPHY

Much of the marine interest on the Gulf coast tends to center on the shallow waters. There are many bays, lagoons, and inlets of great importance to fishing, navigation, recreation, oil recovery, and other activities. Each of these presents its own peculiar problems, and extensive investigations have been carried on in many of them. A recent publication indicating the nature of this work is that of Collier and Hedgpeth (1950). A good bibliography is included indicating the variety of studies which are important in determining the physical characteristics of such regions.

Many analyses of shallow water areas have been conducted for private sponsors, and the results are not yet available. However, they are gradually being released for publication.

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LIGHT PENETRATION IN THE GULF OF MEXICO

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Although the interest and study of submarine illumination has increased throughout the past years, there has not been a proportionate increase in investigation of this subject in the Gulf of Mexico. This paper will attempt to summarize the present knowledge and recent efforts in underwater illumination as applied to this area. It is hoped that the meagerness of the information will be an incentive to future endeavor.

The major part of the known data presented here was calculated from Secchi disc depths. Clarke (1941) points out that Secchi disc determinations are in reasonable accord with measurements obtained from the photronic photometer. The relationship of $K=1.7/D$, where "D" equals the depth in meters when the disc just disappears and "K" denotes the coefficient, was introduced by Poole and Atkins (1929) to convert Secchi disc values into extinction coefficients. The standard equation, $\frac{I}{I_0}=e^{-KL}$, where L is the depth of water expressed in meters in which the intensity of illumination is lowered from I_0 to I, is of advantage for further manipulation of the extinction coefficient.

Several institutions located in the area have studied illumination in the Gulf, but their figures are not yet available.

E. R. Fenimore Johnson, under the auspices of the Smithsonian Institution, conducted studies dealing with the translucence of water as related to visual and photographic transparency in the area under discussion. This information is at present being prepared for publication.

Table 1 represents submarine illumination data that are available at the time of writing. Source material marked WHOI represents information from the Woods Hole Oceanographic Institution's files; D indicates *Dana* reports (Schmidt 1929). The footnoted entries denote photronic photometer derived extinction coefficients.

Taylor (1928), in connection with his algal studies in the Dry Tortugas area, recorded data obtained from the Secchi disc. This information

TABLE 1.—*Submarine illumination data according to the Woods Hole Oceanographic Institution (WHOI) and* Dana *reports (D)*

Date	Latitude (N.)	Longitude (W.)	Secchi disc "K"	Source	Remarks
Feb. 1, 1922	21°49′	85°41′	0.077	D	Station 1221.
Mar. 22, 1938	23°13′	82°19′	[1] .049	Series 460	0 to 100 M.
			[1] .054	WHOI	89 to 150 M.
Feb. 4, 1922	23°13′	82°21′	.052	D	Station 1229.
Feb. 3, 1922	23°40′	82°31′	.065	D	Station 1227.
Aug. 27, 1943	24°25.8′	81°47.9′	<.11	WHOI	
Aug. 10, 1943	24°26.7′	81°57.7′	.35	WHOI	
Aug. 3, 1943	24°27.7′	81°48.1′	.146	WHOI	
Aug. 11, 1943	24°29.8′	81°48.3′	.265	WHOI	
Aug. 10, 1943	24°30.2′	81°48.3′	.35	WHOI	
Aug. 3, 1943	24°30.5′	81°48.3′	.144	WHOI	
No date	24°32′	81°48.5′	.33-1.4	WHOI	
Aug. 7, 1943	24°32.8′	81°49′	.37	WHOI	
Aug. 9, 1943	24°39.9′	81°53.8′	.31	WHOI	
Aug. 6, 1943	24°48′	81°50′	.31	WHOI	
Aug. 6, 1943	24°50′	81°41′	.231	WHOI	
Feb 4, 1951	24°51′	85°58′	.074		Stetson Station, No. 1.
Mar. 16, 1947	24°59′	87°47.5′	.09	WHOI	
Aug. 4, 1943	25°03.5′	81°39.75′	.231	WHOI	
Feb. 24, 1947	25°24′	93°43′	.07	WHOI	
July 19, 1943	27°35.8′	82°55.6′	.124	WHOI	
July 19, 1943	27°36′	82°51.7′	.266	WHOI	
July 21, 1943	27°37.2′	82°39.2′	.464	WHOI	
Jan. 26, 1947	27°38′	93°53′	.08	WHOI	
July 21, 1943	27°30.1′	82°36.6′	.62	WHOI	
July 22, 1943	27°45.4′	82°31.5′	.62	WHOI	
July 23, 1943	27°47.2′	82°32.4′	.62	WHOI	
July 22, 1943	27°48.5′	82°34.7′	.699	WHOI	
July 26, 1943	27°50′	96°27′	.098	WHOI	
July 22, 1943	27°50.6′	82°33.7′	.62	WHOI	
July 27, 1943	28°00′	90°46.19′	.168	WHOI	
July 15, 1943	28°16′	96°18′	.14	WHOI	

See footnote at end of table.

TABLE 1.—*Submarine illumination data according to the Woods Hole Oceanographic Institution (WHOI) and* Dana *reports (D)*—Continued

Date	Latitude (N.)	Longitude (W.)	Secchi disc "K"	Source	Remarks
July 25, 1943	28°17′	96°15′	.14	WHOI	
Apr. 25, 1945	28°35.6′	90°03′	.28	WHOI	
Apr. 20, 1945	28°37.2′	89°46′	.35	WHOI	
Oct. 5, 1942	28°43′	95°20′	.174	WHOI	
Apr. 13, 1945	28°51.6′	89°39′	12.1	WHOI	
Apr. 13, 1945	28°53′	89°33′	12.1	WHOI	
July 15, 1943	28°54′	95°14′	1.39	WHOI	
Apr. 20, 1945	28°54.8′	89°34′	1.6	WHOI	
July 19, 1943	28°55.3′	95°15.7′	1.39	WHOI	
July 5, 1943	29°02′	94°45′	1.86	WHOI	
Apr. 10, 1937	29°08′	88°39′	[1] .16	WHOI	2 to 6 M.
			[1] .88	Series 441	6 to 24 M.
			[1] .058	do	24 to 81 M.
Mar. 29, 1945	29°09′	88°56′	11.3	WHOI	
Apr. 11, 1937	29°14′	87°48.5′	[1] .054	WHOI	2 to 95 M.
			[1] .039	Series 442	95 to 169 M.
			[1] .047	do	Average 2 to 169 M.
Apr. 9, 1937	29°16′	88°50′	.19	WHOI	2 to 6 M.
			.10	Series 440	20 to 53 M.
Mar. 29, 1945	29°24′	88°01′	.74	WHOI	
Apr. 9, 1937	29°27′	88°48′	[1] .22	Series 439	2 to 25 M.
July 10, 1943	29°29′	93°41′	.23	WHOI	
No date	29°30′	94°80′	1.90	WHOI	
Aug. 10, 1943	29°41′	94°59′	5.60	WHOI	
June, July (no date)	29°42′	93°52′	1.4–5.7	WHOI	
Aug. 10, 1943	29°42.33′	94°59.25′	5.60	WHOI	
Aug. 10, 1943	29°42.5′	95°01.25′	5.60	WHOI	
June–September 1943	30°35′	88°00′	.19–1.9	WHOI	

[1] Photronic photometer derived extinction coefficients.

was reported as the depth in which the disc disappeared. These are converted here into extinction coefficients These values are entered in table 2. More detailed information for 51 values in this area is tabulated in the same paper by Taylor.

TABLE 2.—*Extinction coefficients of the Dry Tortugas area based on locations and data of Taylor (1928)*

Station	Secchi disc "K"
Lagoon	0.227–0.134
Outside of reefs	.207– .121
Outside island group	.089– .064
Gulf Stream (15 to 20 miles offshore)	.067– .047
East of Loggerhead Key	.189– .150
West end of Garden Key Channel	.227– .174

Clarke (1938) calculated the extinction coefficients for a series of stations east of the Mississippi Delta. These values are indicated in table 1 as series 439 through 442.

For security reasons, Hulburt's paper (1940) on transparency and visibility of submerged objects in the Key West sector has been classified.

Bumpus and Clarke (1947) have connected equal points of known "K" values on a chart which includes the Gulf of Mexico. It must be remembered that these lines are based on very few observations, and considerable interpolation was necessary.

The Special Scientific Reports, Fisheries No. 8, by Butler (1949), and No. 14, by Butler and Engle (1950), of the United States Department of the Interior contain turbidity indices for selected points of the Mississippi Sound and Lake Pontchartrain. Turbidity is expressed as the percentage–transmission of light through the sample. No correlations with extinction coefficient values or direct Secchi disc measurements are presented.

It is obvious that the transparency data for the Gulf of Mexico are quite inadequate to meet the increasing demands of researchers.

It is admitted that the Photronic photometer is more accurate than the Secchi disc methods of determining the extinction coefficients, but it is also more time consuming. It is suggested, therefore, that the Secchi disc be used. Not more than 2 or 3 minutes are required to lower the white disc (usually 20 or 25 cm. in diameter) until it disappears, and to record the depth. The whole operation is simple and can readily be carried out by unskilled persons.

In view of the limited transparency observations in the Gulf of Mexico it would be difficult to draw accurate comparisons with other areas.

I am indebted to many members of the staffs of the Woods Hole Oceanographic Institution and the University of Miami Marine Laboratory, in particular to Dean F. Bumpus and H. B. Moore for placing their files at my disposal.

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DISTRIBUTION OF CHEMICAL CONSTITUENTS OF SEA WATER IN THE GULF OF MEXICO[1]

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Earliest records of chemical analyses of Gulf of Mexico waters were published by biologists and biochemists who studied the sea water composition as one ecological factor in the complex environment of the marine organisms with which they were concerned. Much of this early work was centered at the Carnegie Institution laboratory at the Dry Tortugas near the western end of the Florida Keys. First oceanographical studies of the chemistry of the water were confined to the system of currents flowing across the southeastern corner of the Gulf from the Yucatán Channel to the Straits of Florida. Practically all analyses of offshore and subsurface waters of the Gulf were made in 1914, 1922, 1932, 1934–39, 1942, and since 1947.

The chemical data are summarized here in order of the decreasing amount of published information: salinity, oxygen, phosphorus, nitrate, nitrite, pH, alkalinity and carbon dioxide components, copper, and miscellaneous chemical constituents.

SALINITY

Salinity is defined as the total amount of dissolved solid material in grams contained in 1 kilogram of sea water when all the carbonate has been converted to oxide, the bromine and iodine replaced by chlorine, and all organic matter completely oxidized. In practice, it is calculated from the chlorinity which is determined by titration with silver nitrate solution. Less accurate salinity values are calculated from densities determined with hydrometers. Both salinity and chlorinity are reported as parts per thousand by weight, using the symbol, °/oo.

In the shallow waters of the Dry Tortugas, in the years 1910 to 1913, Dole (1914) reported salinities ranging from 35.41°/oo to 36.11°/oo. Diurnal and tidal changes in salinity in the same area in 1919 indicated a wider range, 34.61°/oo to 36.29°/oo (Wells 1922).

In the bays along the coast of Texas the wide salinity variations cause recurring mass mortality of marine animals. This situation was reported by Johnson (1882), Rathbun (1895), and Higgins and Lord (1926). Results of detailed surveys of the salinity distribution in the Texas bays in 1926–27 were reported by Galtsoff (1931). Additional studies of salinity along the Texas, Louisiana, and Mississippi coasts were published by Higgins (1931), Riley (1937), Lindner (1939, 1941), Gunter (1945, 1947, 1950), Wise, Winston, and Culli (1945), Price (1947), Geyer (1950), and Collier and Hedgpeth (1950). Alternating floods and droughts cause salinity changes from nearly fresh to 100°/oo, three times that of normal sea water.

In connection with studies of the red tide along the west coast of Florida, salinity data were published by Galtsoff (1948), Gunter, Williams, Davis, and Smith (1948), and Ketchum and Keen (1948). In the open Gulf salinities ranged from 30.6°/oo to 37.0°/oo; in Estero Bay, 21.4°/oo; and near the mouth of the Caloosahatchee River, 12.2°/oo.

In connection with plankton studies in 28 mangrove-bordered inland bodies of brackish water on the west and south coasts of Florida in 1947–48, Davis and Williams (1950) reported salinities ranging from 0.61°/oo to 29.09°/oo.

The present center of Florida's oyster industry, Apalachicola Bay in northwest Florida, was the subject of an 18-month survey of salinity (Ingle 1951; Ingle and Dawson 1951). Annual variations ranged from fresh water to 42.5°/oo Daily, weekly, and tidal variations were considerable.

Apparently the first published salinity records for offshore and subsurface Gulf of Mexico waters are those of Vaughan (1918) who reported salinity values for samples collected at five stations between Havana and Key West from the surface to

[1] Contribution No. 101, from the Marine Laboratory, University of Miami.

1,700 meters by the United States Coast and Geodetic Survey steamer *Bache* in March 1914. Salinities of two surface samples collected a little farther east in January and February 1919 were reported by Mayor (1922). Stations taken by the Danish research vessel *Dana* across the Havana section in 1922 provided data for a salinity profile (Nielsen 1925; Schmidt 1929; Jacobsen 1929). Composition of two surface samples collected in July 1922 in the Gulf Stream south of the Dry Tortugas was reported by Lipman (1929).

The Havana section was studied again in February 1932 on the Yale Oceanographic Expedition aboard the schooner *Mabel Taylor* (Parr 1935). Expeditions from the Woods Hole Oceanographic Institution aboard the research vessel *Atlantis* have made studies of the Havana section in March 1934 (Bulletin Hydrographique, 1935), February and April 1935 (Bulletin Hydrographique, 1936; Seiwell 1938), March 1938 (Montgomery 1941), and May 1939 (Riley 1939). The vertical distributions of salinities across the Havana sections in 1922, 1932, and 1934 were summarized in profiles by Parr (1935, pp. 42–44, 71). Below 100 meters the isohalines generally sloped downward toward the Cuban coast. In the middle of the Straits the salinity generally increased from 35.83°/oo at the surface to 36.68°/oo at 200 meters, then decreased to a minimum of 34.87°/oo at 800 meters, and thereafter increased only slightly to 34.97°/oo at 1,600 meters.

The next most thoroughly studied part of the Gulf of Mexico is the Yucatán Channel where the Caribbean Current enters the Gulf between western Cuba and Mexico. This section was studied in 1922 from the *Dana* (Schmidt 1929; Jacobsen 1929), in February 1932 from the *Mabel Taylor* (Parr 1935), and from the *Atlantis* in May 1933 (Bulletin Hydrographique, 1934; Parr 1937; Rakestraw and Smith 1937) and March 1934 (Bulletin Hydrographique, 1935; Parr 1937). The vertical distributions of salinities across the Yucatán Channel in 1933 and 1934 were summarized in profiles by Parr (1937, pp. 42–43). Here, also, the isohalines generally sloped downward toward the Cuban coast. The vertical distribution of salinity was similar to that described above for the Havana section. Comparison of the average temperature–salinity correlation curves for the Yucatán Channel and the Havana section of the Straits of Florida led Parr (1935) to conclude that the water mass entering the Straits of Florida is identical with that which passed through the Yucatán Channel except for a very small layer of "Gulf type" water at the surface on the left (Florida) side of the main current.

Parr's (1935) report on the expedition of the *Mabel Taylor*, February to April 1932, included a map showing the locations of the 68 stations occupied in the Gulf, complete temperature and salinity data, salinity profiles of 5 sections across the main parts of the Gulf, maps of salinity distribution in upper 50 meters and at 200 meters, graphs of vertical distribution of salinity, and temperature-salinity correlation curves. The expedition was not provided with unprotected reversing thermometers and therefore had no means for accurate determination of the depths of observations. The highest salinities (above 36.25°/oo) in the upper 50 meters were found in the shallow waters off the west coast of Florida and the Campeche Bank. Most of the offshore water in this surface layer had salinities between 36.00°/oo and 36.25°/oo. Low salinities (below 33°/oo) were found along most of the northern regions of the Gulf, and very low (less than 24°/oo) salinities were found near the mouth of the Mississippi River and to the west from the delta region. At a typical station in the western Gulf (25°46′ N., 92°31′ W.) the salinity decreased slightly from 36.16°/oo at the surface to 36.12°/oo at 50 meters, then increased to the maximum of 36.31°/oo at 100 meters, then decreased to the minimum of 34.87°/oo at 600 meters, then increased slightly to 34.92°/oo at 800 meters, below which it remained practically constant down to 3,000 meters.

Dietrich (1939, p. 119) used the 1932 data from the Gulf of Mexico to prepare another map showing the distribution of the maximum salinities, regardless of depth. This showed a continuous layer of high salinity (above 36.7°/oo) water in most of the Caribbean Sea, the northern half of the Cayman Sea, and extending northward into the Gulf to 26°00′ N. and 89°20′ W.

The *Atlantis* occupied stations along several sections of the central and western Gulf in February to April 1935 (Bulletin Hydrographique, 1936). A map showing the locations of these stations was published by Vaughan (1937, p. 21). Vertical distribution of salinity at a typical station in April 1935 in the western Gulf (25°40′ N., 94°23′ W.) was charted by Dietrich (1939, p. 117, fig. 33); it was similar to that described above for the *Mabel Taylor* station about 100 miles farther east.

The *Atlantis* occupied a series of nine stations in the northeast Gulf in March and April 1942 from which salinity data were published (Bulletin Hydrographique, 1950). The same vessel occupied a series of 24 stations in the northwestern and central Gulf, January to March 1947 (Trask, Phleger, and Stetson, 1947).[1]

The research vessel of the Fish and Wildlife Service laboratory at Sarasota, Florida, has occupied stations from Sarasota to Naples and to a distance of 120 miles off shore at approximately monthly intervals since May 1949. Chemical analyses of the water were made for chlorinity, dissolved oxygen, inorganic phosphate, total phosphorus, nitrate, nitrite, and hydrogen ion concentration.[2] The phosphorus data have been published (Graham, Amison, and Marvin, 1954). The other data will be published later.[3]

The Fish and Wildlife Service research vessel *Alaska* began a series of oceanographic cruises in the Gulf of Mexico in 1951. Salinities collected on these cruises are being determined at Texas Agricultural and Mechanical College. They shortly will be made available in a mimeographed form.[4]

DISSOLVED OXYGEN

The first available data on dissolved oxygen content of Gulf of Mexico water seem to be on the results of analyses of water collected at the Dry Tortugas and published by McClendon (1918).

Oxygen determinations were reported when the *Atlantis* occupied stations across the Yucatán Channel in May 1933, March 1934, and February 1935; across the Havana section of the Florida Straits in March 1934, February and April 1935, August 1938, and May 1939; and in the main part of the Gulf in February to April 1935. The oxygen and other data from most of these stations were published in the Bulletin Hydrographique in 1934, 1935, and 1936. A graph of the vertical distribution of dissolved oxygen in the center of the Yucatán Channel in 1933 was given by Rakestraw and Smith (1937, p. 9), and a map showing the locations of the stations was published by Vaughan (1937, pl. 11).

Seiwell summarized the oxygen data from the 1933–1935 *Atlantis* stations in the eastern half of the Gulf with profiles across the Straits of Florida and the Yucatán Channel (Seiwell 1938, figs. 6, 15) and gave charts of the horizontal distribution of oxygen at 100, 250, 500, 750, 1,000, 1,500, and 2,500 meters (Seiwell 1938, figs. 7, 8, 11, 14, 16, 17, 20). Vertical distribution of oxygen at a typical station in the western Gulf (25°40′ N., 94°23′ W.) was charted by Dietrich (1939, p. 117, fig. 33): from about 4.8 cubic centimeters per liter at the surface, it increased slightly to about 4.9 cubic centimeters at 25 meters, then decreased to a minimum of 2.35 cubic centimeters at 300 meters, then increased gradually to about 5.0 cubic centimeters at 2,400 meters, and thereafter remained constant to 3,400 meters. Dietrich (1939, p. 120, fig. 35) also presented a chart showing the distribution of minimum oxygen concentration, regardless of depth, in all but the southwest part of the Gulf. The lowest oxygen concentrations (below 2.5 cc. per liter) were found in the northwest corner; values below 2.7 cc. per liter were observed north of the Campeche Bank and off the central west coast of Florida.

Riley (1938, 1939) reported oxygen concentrations in surface and subsurface samples in the summer of 1938 at two stations in the Dry Tortugas in depths of 3 and 19 meters, one station in the Florida Straits in the depth of 166 meters, and from two stations in the Havana section of the Florida Straits in May 1939. In presenting a detailed summary of oxygen in the Atlantic Ocean he omitted the Gulf of Mexico (Riley 1951).

Scattered records of oxygen analyses made in connection with studies of animal mortality including the red tide have been published by Gunter (1942), Galtsoff (1948), Gunter, Williams, Davis, and Smith (1948), Connell and Cross (1950).

PHOSPHORUS

The earliest published record of phosphorus content of Gulf of Mexico water is that of Lipman

[1] Salinity data from these stations were kindly supplied by Fred B. Phleger on August 15, 1950. They are also available from data cards on file at the Woods Hole Oceanographic Institution and will probably be published in the Bulletin Hydrographique.

[2] Personal communication from L. A. Walford, December 5, 1950.

[3] Personal communication from Herbert W. Graham, January 3, 1952.

[4] Temperature-salinity relationships are discussed in the article of D. F. Leipper, Physical Oceanography of the Gulf of Mexico, in this book, pp. 119–135.

(1929) who reported results of analyses of two samples of water collected at the Dry Tortugas in July 1922: 1.00 and 4.80 parts phosphate per million parts of water (10.5 and 50 microgram-atoms phosphate-phosphorus per liter).

Information on the vertical distribution of phosphorus in the Gulf of Mexico is very limited. Determinations of phosphate were made on the 16 samples (surface to 1,732 meters) collected at *Atlantis* station 1606 in the middle of the Yucatán Channel in May 1933 (Bulletin Hydrographique, 1934, p. 103). Graphs of the vertical distribution of phosphorus at this station were published by Rakestraw (1936, p. 160, fig. 11) and Rakestraw and Smith (1937, p. 9, fig. 7).[5] The phosphate-phosphorus[6] remained nearly constant at 0.15 µg-atoms/L from the surface to 97 meters, then increased to a maximum of 2.47 at 736 meters, then decreased to 1.71 at 1,732 meters. These data for Yucatán Channel water were used in the charts of horizontal distribution of phosphate at various depths (Rakestraw and Smith, 1937, figs. 10–12).

Horizontal and vertical distribution of phosphate near the mouth of the Mississippi River in March 1937 was reported in tables and a map by Riley (1937, pp. 74, 63). He found about 0.58 µg-atoms/L in the low salinity surface water at the station at the mouth of the river. Phosphate decreased in all directions to an average of 0.14 µg-atoms/L at the stations in the Gulf.

Distribution of phosphate at the Dry Tortugas and in the Florida Straits was reported by Riley (1938, 1939) and Riley, Stommel, and Bumpus (1949, p. 16). Near Loggerhead Key where the depth was 3 meters, the phosphate ranged from 0.015 to 0.10 µg-atoms/L from July 18 to August 2, 1938. At his station midway between Loggerhead and Garden Keys where the depth was 19 meters the phosphate at depths of 1, 5, 10, and 15 meters varied quite differently with depth on 4 days in July 1938 from 0.02 to 0.16 µg-atoms/L. His data from other stations are summarized in table 1.

Riley (1951) presented a detailed summary of phosphorus distribution in the Atlantic Ocean but omitted the Gulf of Mexico, except for his discussion (p. 15) of the tendency for the products of regeneration (phosphate and nitrate) to accumulate in the deep water of the Caribbean-Gulf of Mexico basins because the outflow through the Straits of Florida is shallower than the maximum depth of the inflowing water.

TABLE 1.—*Vertical distribution of phosphate (µg-atoms/L) in the Florida Straits*

Location	Station depth (meters)	Date	Levels below surface at which samples were taken (in meters)							
			1	18	45	90	100	153	200	300
20 miles south of Loggerhead Key	166	Aug. 6, 1938	0.11	0.02	0.12	0.12		1.07		
Midway between Havana and Key West, Station number 3491	1,719	May 15, 1939	.03				0.07		0.33	0.68
Off Matanzas, Cuba, Station number 3486	722	May 11, 1939	.21				.10		.51	

Results of phosphate analyses at various inshore stations in the Tampa Bay area and near the southern tip of the Florida peninsula in 1946, reported by Williams (1947) and Smith (1949), are summarized in table 2.

TABLE 2.—*Phosphate (µg-atoms/L) along Gulf coast of Florida in 1946*

Area	Location of sampling station	Date	Phosphate µg-atoms/L
Tampa Bay	Green Key, Hillsboro Bay	Jan. 30.	8.4
Do	do	June 4.	12.0
Do	1 mile west of Green Key	do	8.4
Do	Terra Ceia Bay	Jan. 29.	.84
Do	Terra Ceia Bay (center)	June 3.	3.60
Do	Terra Ceia Bay (north side)	do	4.80
Cape Sable	¼ mile southwest of Catfish Key, Florida Bay.	Mar. 9.	.03
Do	Conchie Channel, Florida Bay	do	.03
Do	East River, east of Whitewater Bay.	May 6.	.03

In connection with studies of the red tide along the Gulf coast of Florida in 1947 made during and

[5] There appears to be some confusion regarding units in the three publications dealing with this phosphorus data. The raw data in the Bulletin Hydrographique are reported in milligrams phosphate per cubic meter. When these figures are divided by 95, the corresponding unit is milligram-atoms per cubic meter or microgram-atoms per liter. The scale for fig. 11, p. 160 of Rakestraw (1936) indicates phosphate from 0 to 1.5 microgram-atoms per liter, but the scale for fig. 7, p. 9 of Rakestraw and Smith (1937) indicates phosphate from 0 to 3 milligram-atoms per liter. It is believed that the units in the last paper should be either microgram-atoms per liter or milligram-atoms per cubic meter, which are numerically equal. Later papers report this same data in microgram-atoms per liter (Sverdrup, Johnson, and Fleming, 1942, p. 241) or milligram-atoms per cubic meter (Riley, Stommel, and Bumpus, 1949; Riley, 1951).

[6] Phosphate data reported in this section have been corrected for salt error by multiplying any uncorrected values by 1.15 (Cooper 1938, p. 177; Robinson and Thompson 1948, p. 36).

after the blooming of *Gymnodinium brevis*, the concentrations of inorganic phosphorus were found as high as 7.4 µg-atoms/L and total phosphorus (particulate organic, dissolved organic, and inorganic) up to 20.4 µg-atoms/L in the amber colored water (Ketchum and Keen 1948, p. 18; Gunter, Williams, Davis, and Smith, 1948, p. 319: Galtsoff 1948, p. 20; Smith 1949, p. 5).

These unusually high phosphorus concentrations suggested the need for more detailed information on horizontal, vertical, and seasonal distribution of phosphorus compounds to clarify the fundamental causes of the red tide. Accordingly, when the research program of the Fish and Wildlife Service laboratory in Sarasota, Florida, was planned studies of the distribution of total, inorganic, and organic phosphorus were given primary attention. Results of a detailed survey at 13 stations in the rivers, along the middle Florida coast, and 120 miles west to the 100-fathom line from May 1949 to August 1950 have been published (Graham, Amison, and Marvin, 1954). They show a gradual decrease in phosphorus content of the surface water with increase in distance from shore. The phosphorus-rich waters discharged from the Peace River did not affect, however, the local Gulf waters to any measurable degree. Beyond 14 miles from shore the concentration of total phosphorus in the surface water was usually below 0.25 µg-atoms/L and inorganic phosphorus was usually below 0.10 µg-atoms/L. Larger quantities of phosphorus, mostly inorganic, were found at depths below 50 meters. Occasional upwelling did not seem to influence the phosphorus content of the euphotic zone. There was no evidence of the bottom sediments contributing any appreciable quantities of phosphorus to the water. Local concentrations of the planktonic blue-green alga, *Trichodesmium*, appeared to be associated with high concentrations of total phosphorus.

NITRATE-NITROGEN

Studies of nitrate distribution in the Gulf have generally paralleled those of phosphate reviewed above. Vertical distribution of nitrate in the middle of the Yucatán Channel in May 1933 (Bulletin Hydrographique, 1934, p. 103) was indicated in a graph by Rakestraw (1936, p. 160, fig. 11) and Rakestraw and Smith (1937, p. 9, fig. 7).[7] The nitrate decreased from 2.4 µg-atoms/L at the surface to 1.4 µg-atoms/L at 49 meters, then increased regularly to a maximum of 37.1 µg-atoms/L at 736 meters, then decreased to 24.2 µg-atoms/L at 1,732 meters. These data for Yucatán Channel water were used in the charts of horizontal distribution of nitrate at various depths (Rakestraw and Smith, 1937, figs. 14–16).

Although no nitrate determinations were made on Gulf waters near the mouth of the Mississippi, Riley (1937, p. 69) reported the following data (supplied by A. A. Hirsch of the New Orleans Sewerage and Water Board Company) which are 1935 average values for the Mississippi River water at New Orleans:

Ammonia nitrogen	20 mg/m^3
Albuminoid nitrogen	350 mg/m^3
Nitrite nitrogen	5 mg/m^3
Nitrate nitrogen	200 mg/m^3

Nitrate data for two stations in the Florida Straits reported by Riley (1939, p. 161) are summarized in table 3.

TABLE 3.—*Vertical distribution of nitrate–nitrogen (µg-atoms/L) in the Florida Straits*

Location	Station depth (meters)	Date	Levels below surface at which samples were taken (in meters)			
			1	100	200	300
Midway between Havana and Key West, Station No. 3491	1,719	May 15, 1939	1.70	0.31	0.93	14.3
Off Matanzas, Cuba, Station No. 3486	722	May 11, 1939	1.00	.50	2.21	------

Riley, Stommel, and Bumpus (1949, p. 16, fig. 6) used these surface values for southeastern Gulf water in their summary chart and discussed the origin of Caribbean water from the nutrient-poor Equatorial and Antilles Currents. They explained, however, that the Caribbean "also receives a substantial draught of Antarctic intermediate water, which is very rich, particularly in nitrate. The maximum concentration of this substance at a depth of about 800 meters in the Caribbean (and possibly the Gulf of Mexico) exceeds the amount found anywhere else in the western North Atlantic." Some of this may be accumulated products of regeneration, as suggested for phosphate (Riley 1951).

[7] There appears to be a confusion of units for expressing these nitrate data parallel to that discussed for phosphate in footnote 6.

NITRITE-NITROGEN

Distribution of nitrite-nitrogen in the Gulf of Mexico is almost unknown except for a single station in the Yucatán Channel and a few analyses of surface water along the Florida west coast made in 1946–47 by Williams (1947) and Gunter, Williams, Davis, and Smith (1948), (table 4).

TABLE 4.—*Nitrite-nitrogen along Gulf coast of Florida, 1946–47*

[Observations by Williams, Gunter, Davis, and Smith]

Area	Location	Date	Nitrite-nitrogen µg-atoms/L
Tampa Bay	Green Key, Hillsborough Bay	Jan. 30, 1946	0
Do	do	June 4, 1946	0
Do	1 mile west of Green Key, Hillsboro Bay.	do	0
Do	Terra Ceia Bay	Jan. 29, 1946	0
Do	Terra Ceia Bay (center)	June 3, 1946	.1
Do	Terra Ceia Bay (north side)	do	.1
Cape Sable	¼ mile southwest of Catfish Key, Florida Bay.	Mar. 9, 1946	.2
Do	Conchie Channel, Florida Bay.	do	.2
Do	East River, east of White-water Bay.	May 6, 1946	0
Key West	2½ miles north of Content Keys.	Apr. 12, 1947	0
Do	2 miles north of Barracuda Keys.	do	0

Vertical distribution of nitrite at *Atlantis* station 1606 in the middle of the Yucatán Channel May 4, 1933, depth 1,911 m., reported in the Bulletin Hydrographique (1936, p. 103) and by Rakestraw (1936, p. 149, table 9)[8] is summarized in table 5.

TABLE 5.—*Nitrite-nitrogen in the Yucatán Channel*

Depth (meters)	Nitrite-nitrogen µg-atoms/L	Depth (meters)	Nitrite-nitrogen µg-atoms/L
0	0.135	300	0.02
25	.01	400	.01
50	.01	500	.01
100	.11	600	.01
150	.035	800	.01
200	.03		

HYDROGEN ION CONCENTRATION (pH)

The hydrogen ion concentration of sea water at the Dry Tortugas from the surface to 35 meters varied between the pH values of 8.1 and 8.28 (McClendon, 1916a, 1916b, 1918; Mayor, 1922). Published data on vertical distribution of pH in deeper waters of the Gulf are limited to those taken at *Atlantis* station 1606 in the middle of the Yucatán Channel May 4, 1933. They were reported in the Bulletin Hydrographique (1936, p. 103), corrected for depth to represent conditions *in situ*, and diagrammed by Rakestraw and Smith (1937, figs. 7, 18–20). The pH increased slightly from 8.14 at the surface to 8.17 at 24 meters, then decreased to a minimum of about 7.9 at 736 meters, then increased to about 8.03 at 1,537 meters.

Measurements of the pH of shallow waters of Galveston Bay were made by Wise, Winston, and Culli (1945). Detailed studies of pH distribution at 26 stations in the coastal bays between New Orleans and Biloxi were reported by Gunter (1950); the pH values ranged from 6.66 in Pearl River entering Lake Borgne, to 8.35 in American Bay, off Breton Sound.

Determinations of pH on the sea water collected during and after the red tide (Galtsoff, 1948, pp. 23–24; Gunter, Williams, Davis, and Smith, 1948, p. 319, table 9) indicated no abnormal hydrogen ion concentrations.

ALKALINITY AND CARBON DIOXIDE

The alkalinity or buffer capacity and concentrations of carbonic acid (including the free carbon dioxide), bicarbonate, and carbonate have been studied in Gulf of Mexico water in the Dry Tortugas by Dole (1914), McClendon (1918), Mayor (1922), Wells (1922), and Lipman (1929), and in the Yucatán Channel by Mitchell and Rakestraw (1933), and Rakestraw and Smith (1937, p. 2, table 1; p. 9, fig. 7).

COPPER

According to Riley (1937) soluble copper and copper adsorbed on plankton and detritus is distributed horizontally and vertically in all directions from the mouth of the Mississippi River as far as the 1,000-fathom line. All samples analyzed by him showed the concentrations of soluble copper from 1 to 25 mg/m ^{3} and that of adsorbed copper from 0.3 to 7.2 mg/m.^{3} The high copper values in the surface samples were generally found in waters of low salinity. At the 1,000-fathom station, soluble copper increased from 5 mg/m ^{3} at the surface to 9, 10, 10, and 12 mg/m ^{3} at 100, 300, 600, and 1,800 meters depth, respectively.

MISCELLANEOUS CHEMICAL CONSTITUENTS

Bromine content of the Gulf of Mexico water has been studied in connection with the commercial

[8] The graph of this nitrite distribution (Rakestraw, 1936, p. 160, fig. 11) does not correspond to the figures in the tables.

extraction of this material at the plant constructed in 1940 at Freeport, Texas.

Calcium ranging from 427 to 535 mg/kg was reported by Lipman (1929) in two samples collected at the Dry Tortugas in July 1922. Calcium carbonate precipitation in the water in the Marquesas lagoon when the pH was 8.46 was observed by McClendon (1928, p. 258). The mechanism of this process was studied by various chemists and bacteriologists at the Dry Tortugas and elsewhere (McClendon 1918, pp. 252–258; Gee 1934; Gee and Feltham 1934).

Hydrogen sulfide was indicated in West Galveston Bay by blackening of the white lead paint on boats at a time of animal mortality (Gunter 1942). Tests for hydrogen sulfide were made on the red tide water, but no clearly positive results were found (Gunter, Williams, Davis, and Smith, 1938, p. 320).

Iron ranging from 0.12 to 1.50 mg/kg was reported by Lipman (1929) in two samples from the Dry Tortugas.

Magnesium content of 1,300 mg/kg was reported by Shigley in this book in the Gulf water at Freeport, Texas, where plants were erected for the commercial extraction of this metal from sea water.[9]

Various organic compounds have been reported present in Gulf waters. Gunter (1942) concluded that the mortality of marine organisms in an inshore area was caused by oxygen deficiency associated with decay of organic materials and the accumulation of toxic products of anaerobic decomposition. Riley (1937) reported from 0.23 to 20.60 mg/L of organic matter in the Gulf water in the area near the mouth of the Mississippi River. Both plankton and organic detritus adsorbed significant amounts of copper. Woodcock (1948) studied an unidentified human respiratory irritant, probably a product of the blooming *Gymnodinium brevis* which was carried ashore in minute droplets of sea water. A carbohydrate which showed some of the chemical properties of arabinose was found in concentrations from 2 to 25 mg/L in the natural sea water supply at the U. S. Fisheries Station at Pensacola, Florida (Collier, Ray, and Magnitzky, 1950).

Products of industrial and sewage pollution have been reported in Texas coastal waters (Burr 1945a, b; Wise, Winston, and Culli, 1945).

[9] The extraction of bromine and magnesium from sea water is discussed in an article by C. M. Shigley, The Recovery of Minerals from Sea Water, p. 153.

Potassium concentrations of 404 and 435 mg/kg were reported in two samples of sea water from the Dry Tortugas (Lipman 1929).

Silicon concentrations of 9.80 and 11.10 mg. SiO_2 per kilogram were reported in the same samples (Lipman 1929).

Solids reported by Lipman (1929) from analyses of the two samples of Dry Tortugas water are summarized in table 6.

TABLE 6.—*Solids, mg/kg, in Dry Tortugas sea water*

	Sample No. 1	Sample No. 6
Total solids	35891	37750
Nonvolatile solids	34018	34580
Volatile solids	1873	3170

Distribution of dissolved solids was studied at 26 stations in the coastal bays from New Orleans to Biloxi by Gunter (1950) who reported values ranging from 92 to 29,164 parts per million or milligrams per kilogram.

SUMMARY

Salinity distribution in the Gulf of Mexico is fairly well known except for the general absence of data on seasonal variations in offshore waters.[10] The same could be said of oxygen distribution. Phosphorus distribution is known only for four small areas: Florida Straits, Yucatán Channel, central west coast of Florida, and the Mississippi Delta region. Nitrate, nitrite, pH, alkalinity, carbon dioxide distributions are known only in the Yucatán Channel-Florida Straits corner of the Gulf and there for only one or two seasons of the year. Other chemical data are scarce, scattered, or absent.

It is expected that considerable information will soon become available with the publication of results of studies sponsored by the chemical and oil companies and of those being conducted by the research vessels and in the shore laboratories of the Fish and Wildlife Service.

[10] Seasonal and local variations of chlorinity and salinity in offshore waters of a portion of the Gulf of Mexico are being studied by the American Petroleum Institute (Project 51) through Scripps Institution of Oceanography of the University of California and the Department of Oceanography of the Agricultural and Mechanical College of Texas. Salinity data can be found in the Progress Reports of the Department of Oceanography, Agricultural and Mechanical College of Texas, Project 34, for October 1 to December 31, 1951, and January 1 to March 31, 1952.

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THE RECOVERY OF MINERALS FROM SEA WATER

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Man's hope to develop power from the sea has not yet been realized, but the prospect of recovery of minerals from that mighty storehouse has long since become real. It is the purpose of this writing to trace the history of the extraction of minerals from the seas, to describe recent large commercial projects for recovering elemental bromine and magnesium from sea water, and to briefly discuss a few of the economic factors in such sea water extraction operations.

The total volume of the oceans is estimated to be 320 million cubic miles (Armstrong and Miall, 1946). Although the salinities of the several seas vary somewhat, the average is approximately 35,000 parts of dissolved salts per million, equivalent to 165 million short tons per cubic mile. The oceans of the world thus represent a storehouse of about 50 million billion tons of dissolved materials. The chloride ion represents 54.8 percent of the total salts, the sodium ion 30.4 percent, sulphate 7.5 percent, magnesium 3.7 percent, calcium 1.2 percent, potassium 1.1 percent, carbonate 0.3 percent, and bromide 0.2 percent. Although the sea is believed to contain at least traces of every element, these eight ions account for over 99 percent of the sea water salts; all other elements total less than 1 percent.

Since the sodium and chloride ions represent six-sevenths of the dissolved salts and are the most easily extracted, it is not surprising that they seem to have been involved in the first recovery on record. Sodium chloride, common salt, was undoubtedly the first compound to be removed from sea water and used by man. It is believed that salt was used by cave men at least 5,000 years ago. Salt from sea water is mentioned in Chinese writings about 2200 B. C. Aristotle in his *Meteorologica* wrote of the origin and usefulness of the salts of sea water and described a method of "unsalting" sea water. The ancient Greeks, Romans, and Egyptians were familiar with production of salt by solar evaporation of sea water. Such salt recovery has been common in China, India, and Japan for many centuries, and still continues. Salt from sea water was produced on the Atlantic coast of North America about 1680 and on the Pacific coast in 1852. The Atlantic coast industry was short lived, but that on the Pacific coast has thrived to this time.

The production of crude soda and potash from the ashes of seaweeds was accomplished in Scotland as early as 1720. Iodine was recovered from seaweeds for the first time early in the nineteenth century; magnesia was first prepared on the Mediterranean coast at the end of the century. The records do not indicate any additional progress until 1923 when magnesium chloride and gypsum were produced from the bitterns from solar evaporation of the sea water of San Francisco Bay (Seaton 1931).

These bitterns were first treated with calcium chloride, precipitating the sea water sulfate as calcium sulfate, which was settled and filtered. Concentration of the filtrate, cooling and separation of the residual magnesium sulfate, potash, and other salts by settling and centrifuging, gave a fairly pure magnesium chloride solution which was further concentrated to salable form by boiling. The calcium sulfate resulting from the calcium chloride treatment was washed, dried, and sold as gypsum.

In 1926, the first sea water bromine was recovered on a small commercial scale by chlorinating the San Francisco Bay bitterns, steam stripping, condensing, and purifying the product.

In 1931, the production of potassium chloride by evaporation of the waters of the Dead Sea was inaugurated; in 1932, bromine was recovered on a commercial scale from the residual liquors of the potassium plant using a process similar to that employed for San Francisco bitterns.

Prior to 1933, the survival of the majority of the projects recovering material from sea water depended upon solar evaporation for initial concentration of the valuable sea salts. A few projects depended on adsorption or biochemical concentration as exemplified by the production of soda, potash, and iodine from seaweeds. Of the other likely methods of recovery, precipitation by a specific reagent had been demonstrated in the commercial production of magnesia by liming sea water and in the experimental removal of bromine as the insoluble tribromoaniline. The latter process was developed in 1924 by the Ethyl Gasoline Corporation and carried to large scale experimental work in the floating chemical laboratory, the S. S. *Ethyl* (Stine 1929). Separation by ion exchange processes or by selective volatilization of the material sought had not yet been commercially exploited.

In 1933, a sharp increase in the demand for ethylene dibromide as a constituent of gasoline anti-knock could not be readily met by increasing the output of bromine plants using subterranean brines. Based on experimental work done in anticipation of this need, a plant was constructed by the Ethyl-Dow Chemical Company on the Atlantic coast at Kure Beach, North Carolina, to remove bromine directly from sea water without the prior concentration which had been necessary for the earlier commercial recoveries. The significant feature of this operation was that the small amount of bromine was removed as a gas from the relatively large volume of water; past efforts had largely been directed toward removal of large amounts of water as vapor from the relatively small amounts of dissolved salts.

The original Kure Beach plant was designed to extract 6 million pounds of bromine per year for the production of ethylene dibromide. Through minor additions and process improvements the capacity was increased to nearly 9 million pounds per year. In 1937 the capacity of the plant was doubled, and in 1938, increased again, reaching an output of approximately 40 million pounds per year.

In 1940 a further increase in bromine requirements led to the erection of a plant at Freeport, Texas, to recover bromine from the waters of the Gulf of Mexico. This plant had an initial capacity of about 30 million pounds of bromine per year; a second unit of equal output was built in 1943.

Another milestone in the recovery of minerals from sea water was passed in 1941 when at Freeport, Texas, the first magnesium metal was produced from water of the Gulf of Mexico by the Dow Chemical Company. Although the precipitation of magnesium hydroxide from sea water bitterns and brines and the method of making magnesium metal from magnesium chloride were both well known prior to 1941, it was not until then that these methods were revised and integrated to give an economically feasible process for making metallic magnesium from sea water. The success of the first 18 million pounds per year magnesium plant was shown by the erection of another plant of equal size 1 year later.

In 1942, a 72 million pounds per year magnesium metal-from-sea-water plant was built by the United States Government at Velasco, Texas, as a part of the program planned to meet emergency war-time needs. The plant was designed and run by the Dow Magnesium Corporation. It operated at or above rated capacity for the duration of the war. That sea water represented no handicap as a source of raw material for the newly developed magnesium process was demonstrated by comparative costs published by the Defense Plant Corporation, after cessation of hostilities (Klagsbrunn 1945). The Velasco plant of the Dow Magnesium Corporation bettered by nearly 30 percent the lowest cost achieved by other government plants using more concentrated magnesium sources.

Unfortunately, both this government-owned magnesium project at Velasco and the privately owned bromine plant at Kure Beach were among the war casualties when wartime production capacity encountered reduced peacetime demands. However, economic survival was largely in favor of the sea-water processes. Since World War II the entire United States production of virgin magnesium and an estimated four-fifths of the bromine have been derived from sea water.

The processes which have been successfully used for bromine production at Kure Beach, North Carolina, and Freeport, Texas, and for magnesium at Freeport and Velasco, Texas, are chemically very simple. They have been described in detail in articles by Stewart (1934), Kirkpatrick (1941), Schambra (1945), and others but are worthy of brief review.

There are two bromine extraction processes. Both can achieve recoveries of bromine from sea water approaching 90 percent. The first, called the "alkaline process," is the one which was used for the initial phases of the Kure Beach development. Sea water, which contains 69 parts per million bromine, is carefully screened to remove debris, seaweed, and fish and is continuously pumped to the top of a "blowing out tower," a brick structure packed with wood grids. On its way to the top of the tower it receives chemical additives which convert the nonvolatile bromide of the water to relatively volatile free bromine. The first additive is dilute sulphuric acid which is automatically controlled to reduce the pH of the sea water from 7.8 to 3.5 and thus suppress the hydrolysis of the free halides. The second additive is chlorine gas. This is injected in an amount slightly in excess of the equivalent bromide, converting it to free bromine. At the top of the blowing out tower the treated brine is distributed evenly over the upper layers of wood packing and trickles downward through the packing to outlet ports about 40 feet below. As it slowly moves down, a current of air is drawn into the bottom of the tower by fans at the end of the system; it passes up through openings in the grids and blows the free bromine out of the treated sea water. The latter now passes back to the ocean at some distance from the intake, little changed except for its bromine content.

The bromine-laden air from the top of the blowing out tower next passes to the soda ash absorption tower. This consists of nine spray chambers in series, each chamber having its own separate recycle system for spraying alkaline absorption liquor. Here nozzles at the top of each chamber spray a dilute soda ash solution into the air stream. The sodium carbonate reacts with the bromine and puts it into solution as a mixture of sodium bromide and sodium bromate. Continued recirculation of the alkaline solution builds up the concentration of bromide-bromate, and at regular intervals the solution of highest concentration from the chamber adjacent to the blowing out tower is pumped to a storage tank. The charges of partially brominated alkaline solution in the other chambers are each pumped forward one step, and when the solution in the weak end of the system has been forwarded the last chamber is recharged with a fresh 5 percent soda ash solution.

By means of this batch-countercurrent recirculation a solution is obtained which is nearly eight-hundred-fold more concentrated in bromine than the original sea water.

The production of pure liquid bromine from the sodium bromide-sodium bromate solution is accomplished by a second operation. The solution, which has a slight residual alkalinity, is pumped over a brick-lined scrubber tower where it serves to absorb bromine from the condenser vents. A small amount of steam is added to the bottom of the tower to preheat the liquor for the stripping step. A controlled excess of 60° Be sulphuric acid is then mixed with the liquor, and the reaction between sodium bromide and sodium bromate in the acidic solution produces free bromine. The mixture passes to a continuous steam-stripping column of acidproof construction. The bromine is distilled off and together with excess steam is liquefied in ceramic or glass condensers. The immiscible water layer saturated with bromine is returned to the stripping column. The bromine is purified by distillation, yielding elemental liquid bromine having a purity of 99.7 percent plus. The slightly acid stripping column effluent is added to the incoming sea water to utilize its relatively small acid content.

The second bromine process, known as the "acid process" or "SO_2 process," was developed in 1937 and has been used in all bromine-from-sea-water plants built in the United States since that date. In this method the acidification, chlorination, and blowing out of the sea water are carried out essentially the same as before. Into the bromine-laden air from the blowing out tower is injected a carefully controlled flow of dilute SO_2 gas prepared by burning sulphur in a conventional type burner and cooling the 10–12 percent SO_2 so obtained. The two gas streams are thoroughly mixed by passing through a system of carefully designed baffles, whereupon the bromine reacts with the slight excess of SO_2 in the presence of water vapor to give a mixture of hydrobromic and sulphuric acids in the form of a fine acid mist. The acids are readily scrubbed from the air stream by fresh water in an absorption tower. The resultant acid solution has a bromide content of approximately 7 percent, or 70,000 parts per million. This step thus accomplishes a one-thousandfold concentration of the original bromine of the sea water.

The bromine is removed from the strong acid solution by a method very similar to that employed in the "alkaline process." The acid liquor is pumped over a packed column where it scrubs bromine from the condenser vents. It is preheated in that tower by the addition of live steam. Chlorine equivalent to three-fourths of the hydrobromic acid is added with the steam. The liquid mixture then passes to a steam stripping column where the remainder of the equivalent chlorine is added and the free bromine is steam distilled out of the solution. The bromine-steam vapor from the top of the tower is condensed as before, and purification of the liquid bromine so obtained yields a product of quality equal to that of the first described method.

The hot effluent from the stripping column consists of a mixture of hydrochloric and sulphuric acids. It is added to the incoming sea water and under normal conditions supplies approximately two-thirds of the acid requirements of the blowing-out step.

The factors which determine the competitive position of either or both of these sea water extraction processes differ only slightly from those encountered in the consideration of any economic enterprise. One must principally consider location of raw materials, efficiency of the process, materials of construction, and manpower.

The proper location of a plant utilizing either bromine process is particularly important to the success of the project. A place is required where sea water of high and constant salinity is conveniently available, free from organic contamination, and undiluted by major fresh-water rivers. It must also possess favorable circumstances for disposing of the large quantities of processed water without mixing with the unprocessed water. Where shallow water and variable currents prevail, the intake and effluent systems should be widely separated. Deep water along shore and constantly favorable shore currents lessen the need for such separation. A plant site only slightly above sea level is preferable to reduce pumping costs.

Since both processes depend on vaporization of bromine, and since the vapor pressure of bromine in sea water varies considerably with temperature, a location in a warm climate is highly desirable. Other things being equal, a blowing-out tower handling 25° C. sea water can operate at a higher rate and can produce approximately twice the amount of bromine as the same tower operating at 10° C. The absorption of the alkali process is also susceptible to temperature effects. Absorber losses are five- to fifteen-fold more at 10° C. than at 25° C., depending on the excess alkalinity of the absorbing solution. A location as near as possible to the source of economical raw materials and power and to the point of disposal of the finished product is desirable; but other factors are of secondary importance when compared with the need for favorable oceanographic and climatic conditions.

Because of the relatively large quantities of raw materials which must be handled in order to obtain each pound of bromine, it is necessary that very close operational control be maintained at all points. Since reliable indicators and automatic controls have made a large contribution to the success of the large scale recovery of bromine from sea water (Hart 1947), they must be regarded as integral parts of both processes.

The manufacture of magnesium from sea water is quite different from bromine processes. Magnesium is taken out of the sea water in an alkaline condition instead of acid and is removed by precipitation rather than blowing out.

The process is carried out in 10 well-defined steps. In the first step, sea water containing 1,300 parts per million magnesium is screened as in the bromine process and is continuously treated with an excess of milk of lime. The lime used in the present operation is prepared by calcining oyster shells at 1,200° to 1,400° C. to produce chemical lime of purity over 96 percent, slaking the lime hot, and settling the calcium hydroxide to a heavy slurry. An excess of 20 percent of the theoretical lime is necessary to keep boron compounds in solution.

The boron of the sea water, if absorbed by the hydroxide and carried through the process, gives difficulty in the final electrolysis step. The limed sea water is delivered to standard Dorr settling tanks. There the precipitated magnesium hydroxide settles to the bottom and is drawn off as a thin slurry having a composition of about 12 percent magnesium hydroxide by weight. The overflow from the Dorr tanks is discarded; it represents nearly 98 percent of the water and other materials with which the magnesium was originally associated.

The next step consists of filtering the slurry on Moore batch-type leaf filters. In this step approximately half of the remaining water and soluble materials are separated from the magnesium hydroxide. Filter cake containing 25 percent of magnesium hydroxide by weight is obtained.

The third step provides for neutralization of the alkaline filter cake. The cake is mixed with previously prepared magnesium chloride solution and agitated to make a slurry which can be pumped. It is transferred to a neutralizing tank where an automatically controlled stream of hydrochloric acid is added to exactly neutralize the magnesium hydroxide. Thus, a 15 percent magnesium chloride solution is obtained.

The fourth step consists of evaporation of the magnesium chloride solution to eliminate water and to reduce the solubility of salts picked up from the sea water. Evaporation is accomplished in either of two ways. In the earliest or direct fired method the magnesium chloride solution is sprayed into gas fired chambers. The more recent submerged combustion method accomplishes evaporation by burning a carburated mixture of natural gas and air below the surface of a pool of magnesium chloride solution. In either case, direct contact with the hot products of combustion concentrates the solution to 35 percent magnesium chloride by weight. Direct heating is necessary because of the scaling tendency of the solution.

In the fifth step the unwanted calcium is precipitated from the solution by the closely controlled addition of magnesium sulfate. The treated liquor is held for 24 hours in an agitated tank to encourage crystal growth of the salt and gypsum.

The adjusted evaporator product is then filtered, first through Moore filters identical to those used earlier for the magnesium hydroxide filtration, and then through plate and frame presses for a final polish.

The seventh step of the process is evaporation of the filtered 35 percent magnesium chloride solution to a concentration of approximately 50 percent. Open top, brick-lined steel boiling kettles heated by alloy steam coils are used for this purpose.

In the next stage, the concentrated magnesium chloride liquor at a temperature of 170° C. is transformed into a solid suitable for feeding the electrolytic cells. The hot liquid is sprayed on 6 to 10 times its weight of previously dried solid in a horizontal rotary mixer, producing a white granular material containing about 68 percent magnesium chloride. This is dried with hot recirculated air in a multi-shelf drier, similar in design to a Herreshoff furnace, and becomes a free-flowing granular cell feed of approximate composition $MgCl_2.1.5H_2O$. Part of the dry granular material is returned to the rotary mixer and part is conveyed to the magnesium cells.

The ninth step is electrolysis of the cell feed (Hunter 1944). The electrolytic cells used for this operation are bathtub shaped steel pots of approximately 2,500 gallons capacity, filled with a fused salt mixture consisting of 25 percent $MgCl_2$, 15 percent $CaCl_2$, and 60 percent NaCl at 700° C. Graphite electrodes suspended in the bath serve as anodes; the pots and their internal baffles act as cathodes. Passage of a high amperage, direct current between the electrodes and the pot decomposes the magnesium chloride of the bath to elemental magnesium and chlorine gas. Cell feed is added continuously to maintain the proper bath composition and level. The hot gaseous products are collected under a tightly fitting refractory cell cover, cooled, and piped to the hydrochloric acid plant. The molten magnesium metal rises to the top of the bath where it is trapped by inverted troughs and conveyed to the storage wells in the front of each cell.

The metal is hand dipped from the cells three times daily and cast into the familiar 18-pound notched ingots. Each cell, operating at 60,000 amperes, produces approximately 1,200 pounds of magnesium per day having a purity in excess of 99.8 percent. No other refinement is necessary to meet the specifications for commercially pure magnesium.

The final step of the process consists of converting the chlorine from the cells to hydrogen chloride by high temperature reaction with steam and natural gas in a regenerative furnace. A small amount of unreacted chlorine is reduced by the controlled addition of SO_2 supplied by conventional sulphur burners. The hydrogen chloride and the small amount of H_2SO_4 are absorbed in water, and the resulting acid solution is recycled to the neutralizers for the reaction with $Mg(OH)_2$ previously mentioned.

Since process losses are inevitable, it is necessary to replenish the recycled hydrochloric acid to the extent of about one-half pound per pound of magnesium produced. This may be added as chlorine to the gas stream entering the furnace or as hydrochloric acid at the neutralizers.

The properties and uses of magnesium are well-known but warrant brief comment. It is the lightest structural metal commercially available. It is about one-fourth as heavy as iron and two-thirds as heavy as aluminum. When alloyed with small amounts of other metals, such as aluminum, zinc, and manganese, it has a high strength to weight ratio, it is easily fabricated, and it has good corrosion resistance. These properties make it advantageous for use in light weight structures and equipment such as airplanes, truck and trailer bodies, portable tools, hand trucks, ladders, and others too numerous to mention. The high place held by magnesium in the electromotive series of metals makes it outstanding for sacrificial anodes—in other words, sources of current for the protection of buried or submerged metal surfaces against corrosion. One of the more recently developed uses of magnesium is in the field of ferrous metallurgy. Small amounts of magnesium properly added to cast iron prior to pouring give a so-called "nodular cast iron" which has strength and ductility properties similar to those of steel.

The economic factors involved in the magnesium-from-sea-water operation are somewhat different from those of bromine. From an oceanographic or climatic standpoint, the location is not so critical. The sea water which must be processed per pound of magnesium is only one-twentieth as much as is required per pound of bromine. The water temperature has little effect on the magnesium recovery. More important is a location favorable to the supply of raw materials and power. The convenient availability of lime and abundant and inexpensive fuel and power are obviously essential for competitive operation.

The process can achieve a recovery of 85 to 90 percent of the magnesium in sea water. The performance of each step represents a compromise between high efficiency and high capital cost, and the justifiable recovery must be calculated for the conditions of each plant. The process has the inherent advantage that the majority of the materials can be conveyed by pumping. Most of the steps are continuous and subject to the benefits of automatic control.

The quantities of sea water and oyster shells used in the process are large. In the Freeport plant (following quoted from Schambra, 1945, pp. 4, 6):

"Sea water flows by tidal surge from deep water in the Gulf of Mexico, through the 40 ft. deep channel dredged into the Freeport harbor. Stone jetties at the mouth of the harbor prevent the surf and shore currents from washing sand into the channel. One mile inshore from the harbor mouth, the plant intake withdraws the raw sea water at a depth of 25 ft. A concrete curtain wall holds back the surface water so that the suction opening is actually between −20.0 ft. and −30.0 ft. elevation. In waters of this locality, stratification of high and low density water occurs, even in the range of specific gravity of 1.000 to 1.026, the difference between fresh water and full strength sea water. The use of a curtain wall permits withdrawal of 80% to 90% full strength sea water when the surface may be nearly fresh water. Due to rains and fresh water intrusion from the Brazos River, the sea water at the intake averages 85% of full strength.

At the intake, trash, marine plants, and small fish are removed by a triple screening . . . Four Worthington submerged-propeller axial-flow type pumps, each delivering 70,000 g. p. m., raise the sea water from a varying sea level to a constant head at elevation 9.0 ft. Each pump discharges directly into a unique rotating barrel [Monel] screen . . . made up in wood-framed trays which are bolted to the steel barrel framework. Each tray is carefully insulated from the barrel by rubber gaskets to minimize bi-metal electrolytic corrosion.

Following the screens, the sea water is chlorinated continuously to a residual of 0.2 to 0.5 p. p. m. free halogen. Growth of marine plants, barnacles, and oysters is prevented in this manner . . . Shell [used for the production of lime] is purchased from two dredging companies now working the oyster shell reefs in Galveston bay. Accumulated shells of dead oysters lie in irregular reefs in 1 to 17 ft. of water, with the thickness of the beds varying from 1 to 30 ft. There are millions of tons of usable shell in Galveston and Matagorda Bays alone. Extensive reefs are found off shore in the Gulf. Newly dredged shell contains mud and sand which are removed by washing on the dredge with sea water. The dredge *W. D. Haden* has a capacity of 350 tons per hr. of washed shell. Loaded barges of 800 tons capacity are removed by Diesel tug to the Freeport plant . . . The washed shell is fed either to the storage pile or directly to the kiln feed hoppers . . . Each kiln produces 150 tons of lime per day.[1]

In conclusion, the large-scale recoveries of bromine and magnesium from sea water must not be regarded as merely incidents in the record of scientific progress of the last three decades. They are indicative of a pronounced trend toward using the seas for more of life's needs.

It is natural that this should be so. The seas, covering three-fourths of the earth's surface and

[1] Reproduced with the permission of the American Institute of Chemical Engineers from the Transactions of the A. I. Ch. E., vol. 41, No. 1, pp. 4, 6.

bordering upon every continent, represent a global source of supply. They are practically inexhaustible, for the total quantities of available salts reach astronomical figures and are unquestionably increasing with the daily contribution of the rivers, while other mineral resources are being depleted. The handling of sea water by pumping is unquestionably easier and cheaper than the majority of mining methods. The sea water has relatively stable chemical and physical properties, contributing to constancy of the finished product.

All these things, and more, lead to the inevitable conclusion that the record of past achievements and the vision of man's increasing dependency on the oceans will combine to stimulate the research activities of all the nations toward a more complete utilization of the tremendous resources of the seas.

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