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RECENT OCEANOGRAPHIC INVESTIGATIONS IN THE GULF OF CALIFORNIA

By

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ABSTRACT

Results of seven hydrographic cruises into the Gulf of California during 1956 and 1957 show that the water mass there is characteristic of Equatorial Pacific water though modified by intensive evaporation in surface layers. The combination of wind regime and complicated topographical features plays a predominant role in circulation, upwelling, distribution of temperature, and other hydrographic factors. Seasonal changes are large. An estimate of the water budget indicates that exchange between the Gulf and the Pacific Ocean is of the order of 10^6 m^3/sec. Evaporation in the Gulf is about 5×10^3 m^3/sec. Runoff and precipitation are negligible. Sea-level records were studied and interpreted in terms of geostrophic surface flow. Strong tidal currents in many parts of the Gulf are influencial in mixing the water.

Introduction. The oceanographic aspects of the Gulf of California, one of the least known marginal seas of the North Pacific, are both interesting and complex. Yet little oceanographic research has been done until recently. The Gulf is unique in that it is the only large evaporation basin in the Pacific Ocean. It is characterized by a large annual temperature range and by relatively high salinities. The tidal range at its inner end is impressive and so is the tidal bore that reaches far into the Río Colorado.

Prior to 1956, when the Scripps Institution of Oceanography in collaboration with the South Pacific Fisheries Investigations of the U. S. Fish and Wildlife Service decided to make a series of oceanographic cruises into the Gulf as part of the research conducted under the California Cooperative Oceanic Fisheries Investigations, only two hydrographic expeditions had been undertaken into this region. The first took place in 1889 with the ALBATROSS (Tanner, 1888) and the second, almost 50 years later, with the E. W. SCRIPPS (Sverdrup, 1941). Results from these two cruises and the meteorological aspects of the Gulf region were discussed recently (Roden, 1958).

The aims of the recent cruises into the Gulf from an oceanographic standpoint were twofold: to investigate the seasonal variation of

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[1] Contribution from the Scripps Institution of Oceanography, New Series.

temperature, salinity and oxygen in the upper layers and to determine whether or not any changes in the distribution of properties had taken place in the deeper part of the sea since the last survey in 1939. In addition there were biological investigations which will not be considered here.

Tides and sea level variations in the Gulf have not been studied in detail, but since they are important in understanding the circulation, a brief description of them will be found at the end of this paper.

Data. The stations occupied and the areas covered on the seven recent cruises into the Gulf are shown in Fig. 1 and Table I, respectively. On each hydrographic station, bottle casts were made and temperatures, salinities and oxygens were determined. Bathythermographs were lowered on each station and between stations. The data were processed by the Data Collection and Processing Group of the Scripps Institution of Oceanography; the tabulated data will be published in OCEANIC OBSERVATIONS OF THE PACIFIC, 1956 AND 1957. Sea surface temperatures at coastal stations were obtained from the U.S. Coast and Geodetic Survey (1956) and meteorological information was obtained from Servicio Meteorológico Mexicano (1937, 1938).

Seasonal Variation of Temperature, Salinity and Oxygen at the Surface. One of the outstanding features of the Gulf of California is the large annual range of sea surface temperatures; at Puerto Peñasco in the north the range is about 16 C; at Cabo San Lucas in the south it is about 9 C (Table II). The pronounced seasonal temperature variation is not confined to coastal areas but occurs in offshore regions as well (Fig. 2); agreement between coastal and offshore temperatures is reasonably good. An interesting feature is an area of low temperatures around Isla Angel de la Guarda which is found throughout the year. Along the coast, temperatures are somewhat dependent upon upwelling; in winter low temperatures are generally found along the east coast and in summer along the west coast. There is little information on the year-to-year variation of temperature except that in 1957 temperatures appeared to be somewhat higher than in 1956. The seasonal variation of temperature extends downward from the surface to about 200 m, the average temperature in this depth range ranging between 14 C in winter to 18 C in summer over most of the Gulf.

The seasonal variation of salinity (Fig. 3) is surprisingly small and, except for the southernmost part, the annual range does not exceed 0.2‰. This contrasts sharply with results obtained from shore stations, where the seasonal range is of the order of 1‰ (U. S. Coast and Geodetic Survey, 1954; thus observations along the shore are not

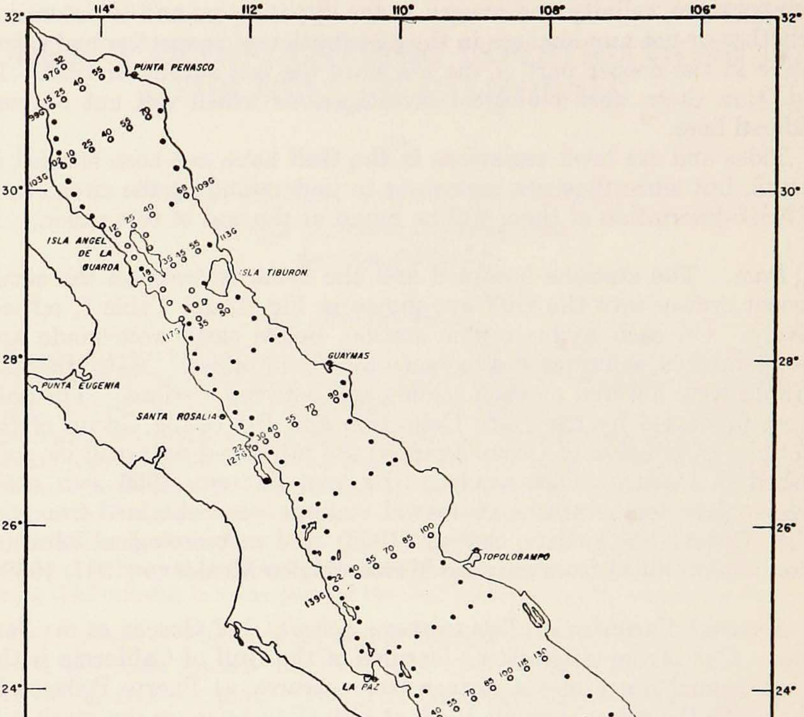

Figure 1. Stations occupied during recent Gulf cruises. Circles represent hydrographic stations, dots net-tow stations. Numbers refer to hydrographic stations.

TABLE I. Chronological list of hydrographic cruises into the Gulf of California.

Time	*Ship*	*Hydrographic casts*		*Properties observed*	*Area covered*
		Number	*to depth*		
11 Mar.–7 Apr. 1889	Albatross	28	bottom	temperature, salinity	Cabo San Lucas northward to Río Colorado.
13 Feb.–19 Mar. 1939	E. W. Scripps	53	bottom	temperature, salinity, oxygen, calcium	Cabo San Lucas northward to Río Colorado.
6 Feb.–17 Feb. 1956	Black Douglas	22	1200 m	temperature, salinity, oxygen	Cabo San Lucas northward to Isla Tiburón.
7 Apr.–23 Apr. 1956	Black Douglas	40	600 m	temperature, salinity, oxygen	Cabo San Lucas northward to Río Colorado.
26 Nov.–16 Dec. 1956	Horizon	59	bottom	temperature, salinity, oxygen	Cabo San Lucas southward to Isla Socorro and Cabo Corrientes.
8 Feb.–23 Feb. 1957	Spencer F. Baird	67	bottom	temperature, salinity, oxygen	Cabo San Lucas northward to Isla Tiburón.
7 Apr.–23 Apr. 1957	Black Douglas	37	600 m	temperature, salinity, oxygen	Cabo San Lucas northward to Río Colorado.
7 June–23 June 1957	Stranger	57	600 m	temperature, salinity, oxygen	Cabo San Lucas northward to Río Colorado.
9 Aug.–26 Aug. 1957	Stranger	57	600 m	temperature, salinity, oxygen	Cabo San Lucas northward to Río Colorado.

TABLE II. SEA SURFACE TEMPERATURES (C) AT SHORE STATIONS

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year*	*Range*
Puerto Peñasco, Son. (1952–1955) USCGS	14.9	15.8	17.8	20.6	23.8	26.3	29.7	31.2	31.0	28.4	22.0	17.1	23.2	16.3
Guaymas, Son. (1950–1953, 1957) USCGS	17.7	18.7	18.8	21.5	25.0	29.3	31.4	31.5	31.3	28.9	24.1	18.7	24.7	13.8
Mazatlán, Sin. (1953–1957) USCGS	21.4	20.1	20.5	21.6	24.1	28.2	29.5	30.0	29.9	28.5	25.1	22.0	25.1	9.9
Cabo San Lucas, B.C. (1957) SIO	20.8	20.5	—	20.6	23.1	23.6	25.9	28.2	29.0	—	26.2	24.4	24.2	(8.5)
La Paz, B.C. (1950–1957) USCGS	19.8	19.9	21.3	22.2	24.0	24.9	27.4	29.1	28.3	28.1	25.1	21.3	24.3	9.3

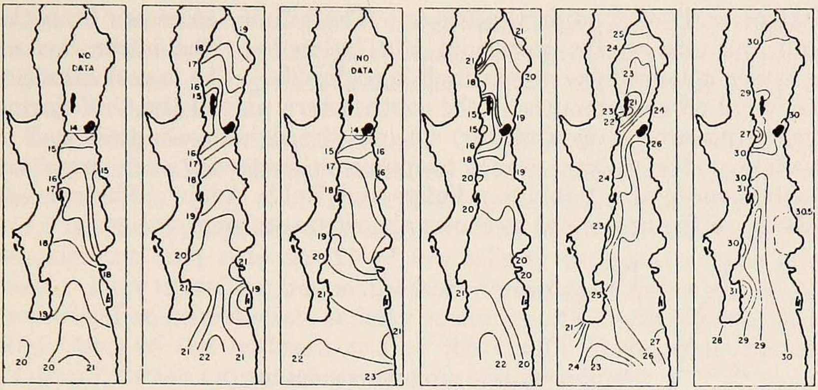

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Figure 2. Horizontal distribution of temperature (°C) at 10 m.

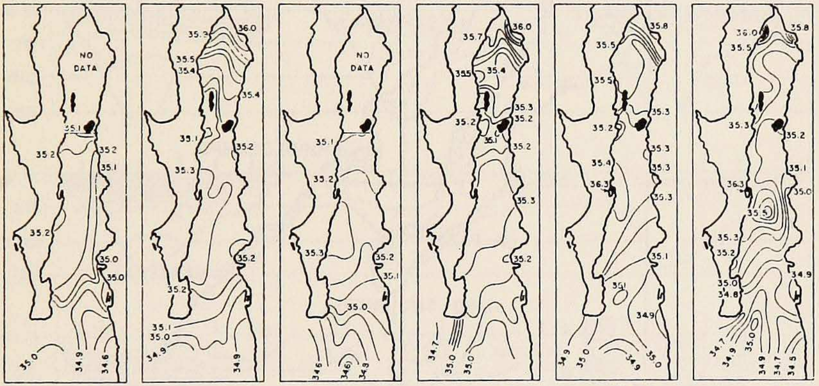

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Figure 3. Horizontal distribution of salinity (‰) at 10 m.

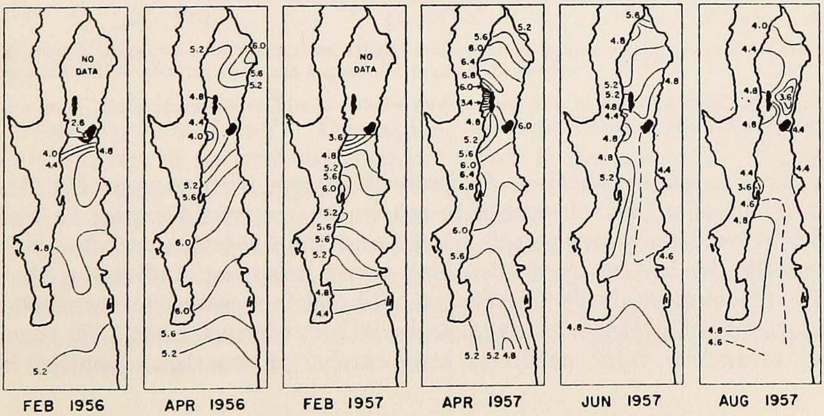

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Figure 4. Horizontal distribution of oxygen (ml/1) at 10 m.

characteristic of conditions offshore. The salinity increases from the Gulf entrance to the mouth of Río Colorado. The latter has no influence upon salinity since runoff is negligible. The lowest salinities are found off river mouths in the southeastern part of the Gulf during the rainy season (July–October) whereas the highest salinities occur in shallow protected bays where evaporation is strong; such areas are Bahía Concepción, Bahía San Felipe and Bahía Adair. The average salinity of the upper 200 m shows almost no seasonal variation.

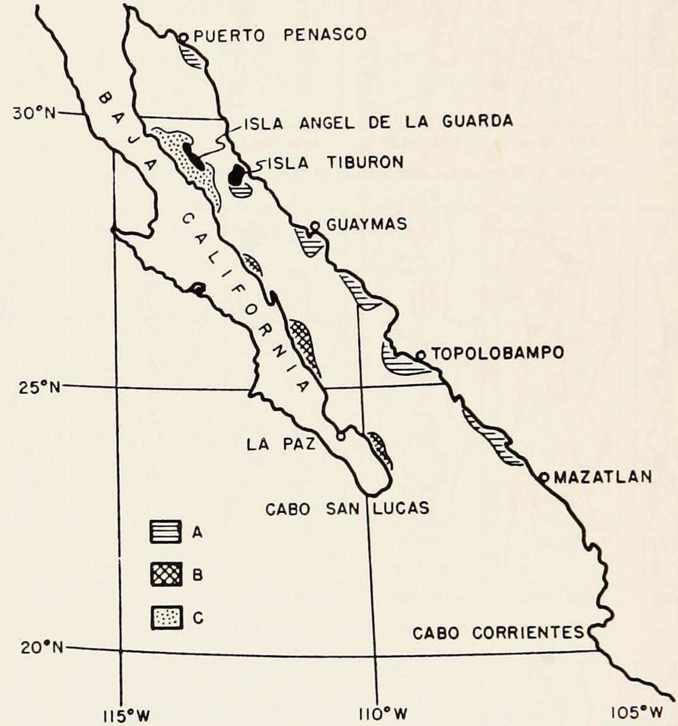

Figure 5. Upwelling areas: a) with northwesterly winds. b) with southeasterly winds. Area c is characterized by strong tidal mixing.

There is some variation of dissolved oxygen with season (Fig. 4). From the solubility of oxygen in sea water one would expect to find the highest concentrations in winter and the lowest in summer, but actually the highest concentrations occur in spring, indicating that biological activity is also important. The surface waters are generally saturated with respect to oxygen, deviations of more than 15% from the saturation value occurring only rarely. A notable exception is found in the vicinity of Isla Tiburón and Isla Angel de la Guarda where undersaturation frequently occurs. Production of oxygen by phytoplankton during the "blooming" season occasionally leads to strong oversaturation.

Upwelling plays an important role. With northwesterly winds upwelling occurs along the east coast and with southeasterly winds along the west coast (Fig. 5). The upwelling areas are mostly found in wind lee of capes, points and islands. The upwelled water is of low temperature, and it is usually of low salinity except along the west coast. Here upwelling frequently leads to higher salinities due to the presence of an intermediate salinity maximum at a depth of about 50 m originating at the northern end of the Gulf. There is no obvious relation between oxygen concentration and upwelling.

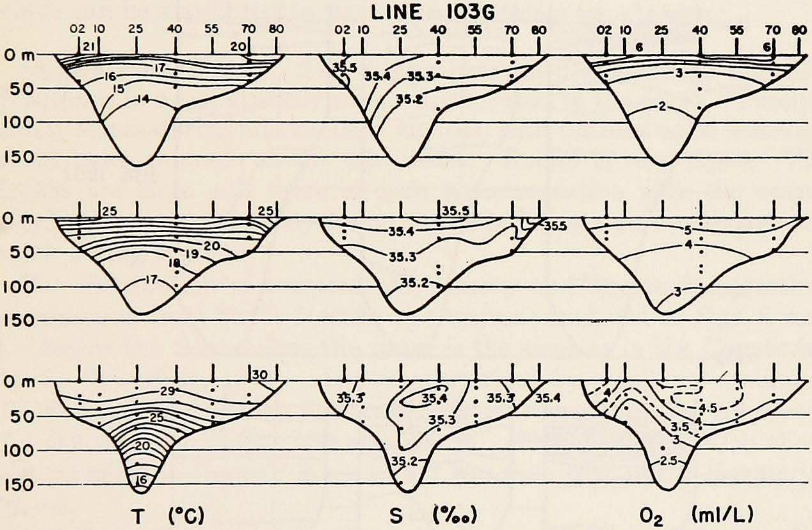

Figure 6. Distribution of temperature, salinity and oxygen in vertical section across the northern part of the Gulf for April, June, and August 1957 in descending order.

Northern Part of Gulf. This region, between Río Colorado and Isla Tiburón, lies in an arid environment which is characterized by large annual temperature ranges and strong evaporation. There is little precipitation (less than 100 mm/year) and runoff is negligible. Winds are predominantly northerly in winter and southerly in summer. The average depth is quite shallow, being about 200 m. An exception is the 1000 m deep trench between Baja California and the islands of Angel de la Guarda and San Lorenzo which is isolated from the rest of the Gulf below 250 m.

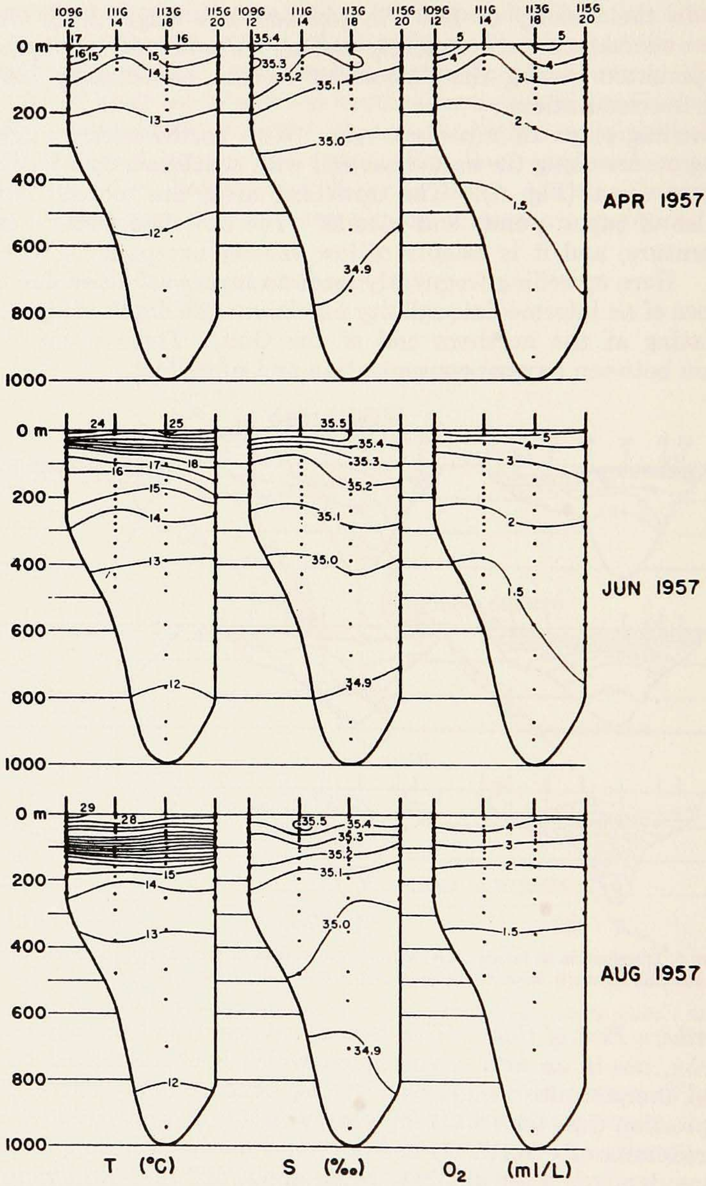

Figure 7. Distribution of temperature, salinity and oxygen in a vertical section along Ballenas Trench.

The distribution of temperature, salinity and oxygen with depth is shown in Fig. 6. Strong temperature gradients between surface and bottom are found during summer months owing to intense solar heating and lack of mixing. Winter conditions have not been thoroughly investigated, but records made at Puerto Peñasco seem to indicate that the water may be almost isothermal (14 C). Salinities, except near the coast, vary between rather narrow limits and are mostly 35.2–35.5‰.

Unusual conditions prevail in the deep trench. Surface temperatures are generally lower here than elsewhere. At depths, temperature, salinity and oxygen (Fig. 7) are much higher than in any other place at that depth. At 1000 m the temperature difference inside and outside the trench is 6°C, the salinity difference 0.4‰, and the oxygen difference 1 ml/L. These features are indicative of intensive mixing which can be attributed to strong tidal currents found there.

Central Part of Gulf. This region between Topolobampo and Isla Tiburón is in a less arid environment than that to the north. Precipitation occurs during late summer months, with the east coast receiving about twice as much as the west coast. Runoff is very slight. The depths are large and there is open communication with the ocean. Winds blow predominantly from the north during winter and from the south during summer.

The distribution of temperature, salinity and oxygen in a vertical cross-section from Santa Rosalía to Cuaymas is shown in Figs. 8 and 9. Below the thermocline the water is the same as in the Equatorial Pacific (Sverdrup, 1941). It is characterized by a salinity minimum (34.50–34.55‰) between 600 and 1000 m and an oxygen minimum (0.1–0.2 ml/L) between 400 and 800 m. The depth at which these minima occur in the gulf is somewhat less than that in the Equatorial Pacific.

Above the Equatorial Pacific water lies a water mass which is distinguished by its higher salinities and which may be called "Gulf water"; this can be looked upon as equatorial water which has been transformed at the surface by evaporation. The salinity and oxygen distributions in the upper layers are very complicated and dependent upon season. Warm temperatures in winter are slightly colder along the east than along the west coast; in summer the opposite occurs This phenomenon can be ascribed to upwelling. In late summer there appears to be, from consideration of continuity and the presence of salinity tongues, a northward flow of low salinity water along the east coast and a southward flow of high salinity water along the west coast, both occurring at subsurface depths of about 50 m.

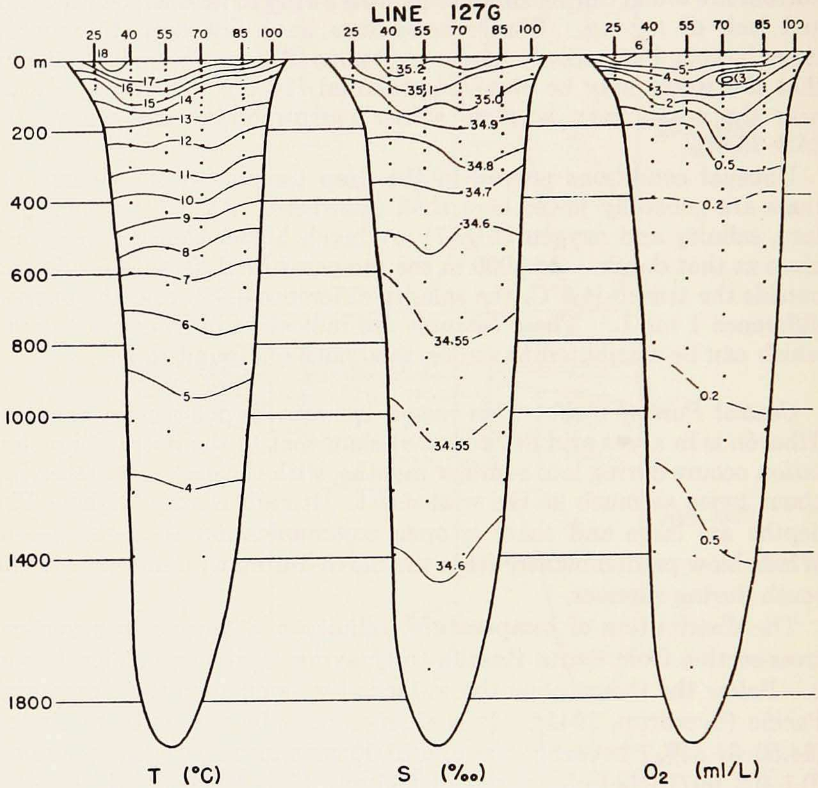

Figure 8. Distribution of temperature, salinity and oxygen in a vertical section across the central part of the Gulf for February 1957.

Southern Part of Gulf. The region between Topolobampo and Cabo Corrientes lies in a moderatley humid environment. Annual precipitation, occurring mostly in late summer and fall, varies between 500 and 1000 mm/year, with less rainfall in the northern part of this region than in the south. During the rainy season there is considerable runoff. Winds are predominantly northerly in winter and southerly in summer. The southern boundary of the Gulf is not well defined, but for oceanographic considerations it can be taken from Cabo San Lucas to Cabo Corrientes. The depths in this part of the Gulf are great, frequently exceeding 3000 m.

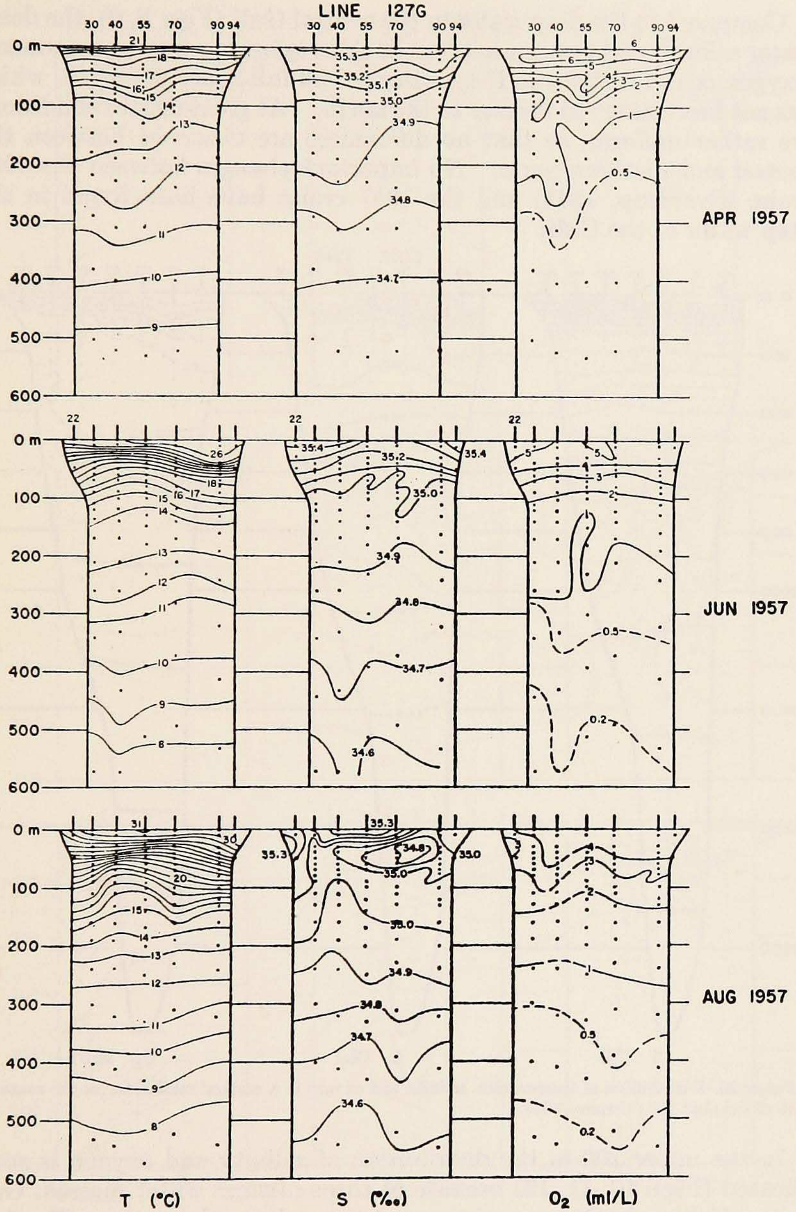

Figure 9. Distribution of temperature, salinity and oxygen in a vertical section across the central part of the Gulf.

Compared to the deep water in the central Gulf (Figs. 8, 9), the deep-water salinity and oxygen minima in this region are more pronounced. Oxygen concentrations in the southern Gulf fall below 0.1 ml/L, which has not been observed further to the north. At great depths conditions are rather uniform, so that no differences are observed between the central and southern parts. No important changes between the 1939 cruise (Sverdrup, 1941) and the 1957 cruise have been found in the deep water of the Gulf.

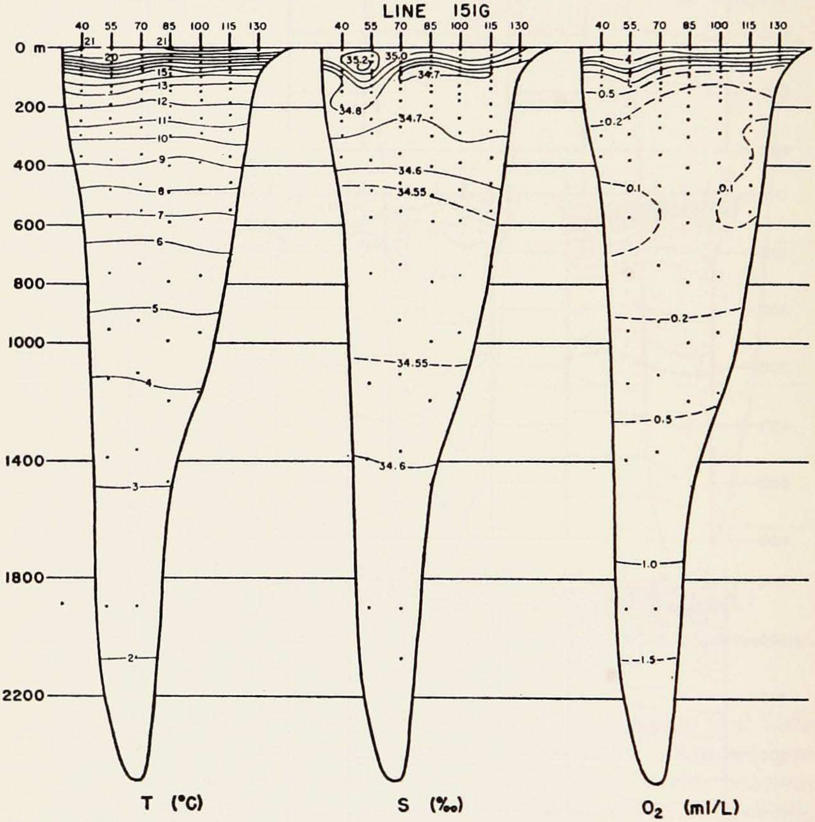

Figure 10. Distribution of temperature, salinity and oxygen in a vertical section across the southern part of the Gulf for February 1957.

In the upper 200 m the distribution of salinity and oxygen is complicated (Figs. 10, 11, 12) because of three distinct water masses: Gulf water, California Current water, and water from the eastern Tropical Pacific. The first is characterized by relatively high temperature and

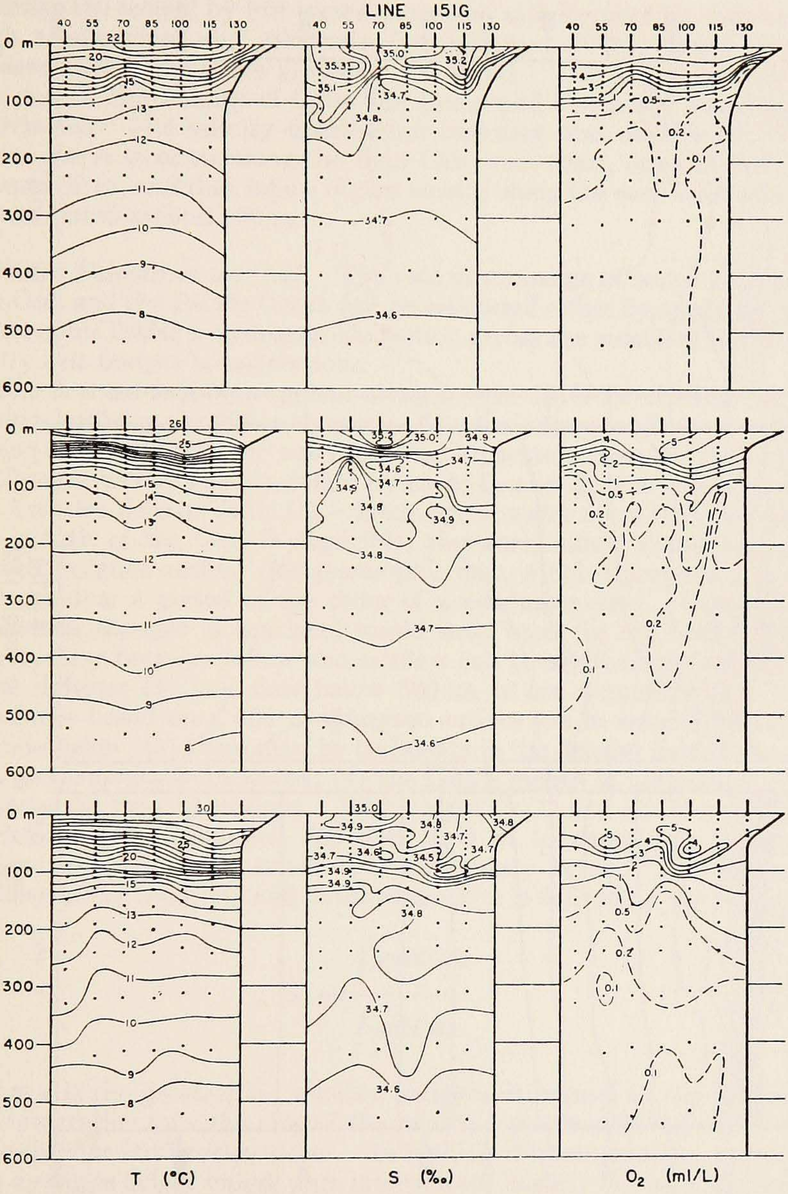

Figure 11. Distribution of temperature, salinity and oxygen in a vertical section across the southern part of the Gulf for April, June and August 1957 in descending order.

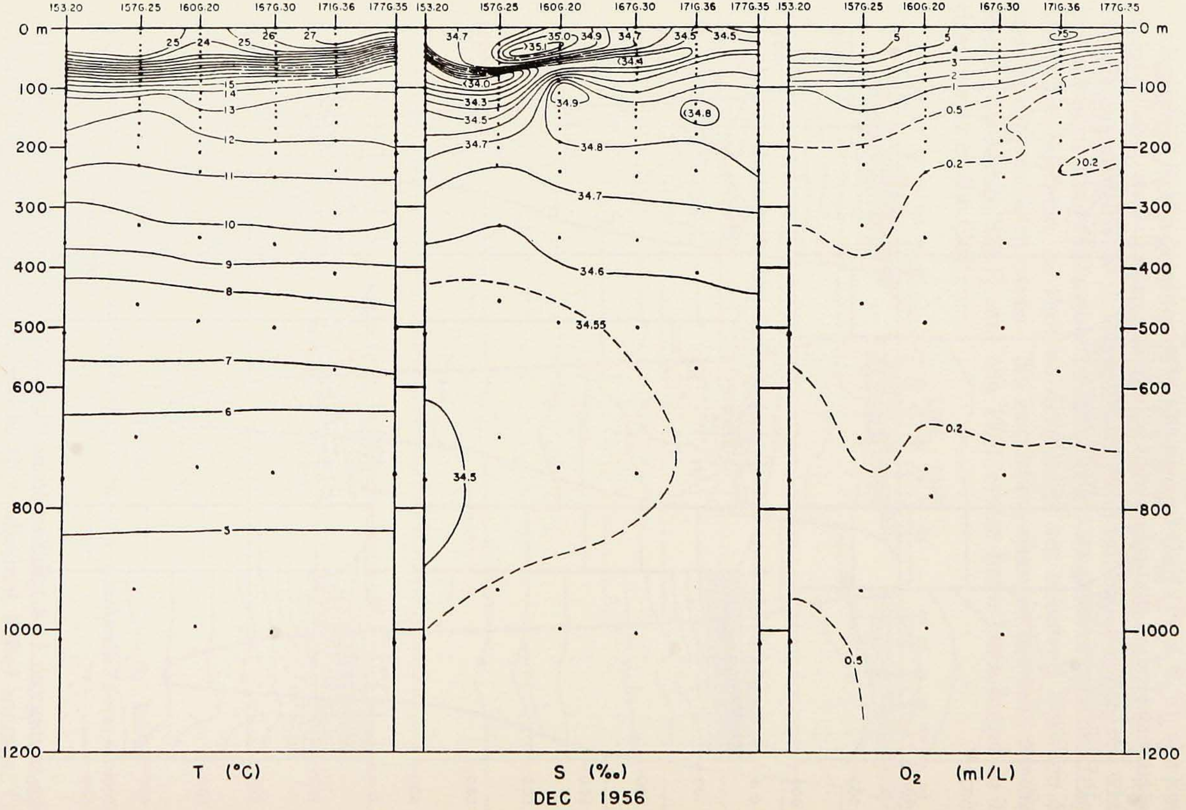

Figure 12. Distribution of temperature, salinity and oxygen in a vertical section from Cabo San Lucas to Cabo Corrientes.

salinity, the second by low temperature and salinity, and the latter by high temperature and relatively low salinity. Where these water masses meet, very sharp gradients are found. This is nearly always the case in the vicinity of Cabo San Lucas and frequently near Cabo Corrientes. The salinity distribution indicates that outflow of Gulf water seems to occur along the Baja California coast, often at depths around 50 m, and that inflow occurs mostly along the east coast and is concentrated around 100 m.

Water Balance in the Gulf. The rate of exchange of water between the Gulf and the Pacific Ocean can be estimated either by applying the geostrophic law to a hydrographic section across the mouth of the Gulf or by salt budget considerations.

The first method was applied along section 151G for the four 1957 cruises, utilizing the 500 m dynamics between adjacent stations. The region of inflowing water was computed separately from the region of outflowing water, and the totals for each, Q_i and Q_o, are tabulated in the first two lines in Table III. Exchange of water other than through the mouth of the Gulf is negligible; therefore, inflow should almost exactly balance outflow (for geostrophic flow, which represents a time average over a period of the order of a pendulum day). Otherwise, ridiculous changes in sea level would soon occur in the Gulf. The discrepancy between inflow and outflow can be ascribed to four principal defects: (1) any flow below 500 m is not accounted for; (2) dynamics based on a 500 m reference surface are in error if there is motion below; (3) there may be transients in the density field that are not geostrophically balanced; (4) the Gulf's mouth is not completely spanned by the end stations. With regard to (1) and (2), the density variation needed between 500 and 1000 m to completely balance inflow and outflow is small and could likely occur. The average salinity of the inflowing and outflowing water is defined by the relation

$$\bar{S} = \frac{\int \rho v S dx\, dz}{\int \rho v dx\, dz}, \tag{1}$$

where v is the geostrophic velocity component normal to the section; the integration over the area of the section is confined to the region of inflowing (or outflowing) water. In making the computation, salinity and dynamic height values were interpolated linearly between stations. For three of the cruises, the outflowing water was more saline than the inflowing, but the opposite is indicated for the June cruise. Of course, this computation is subject to all the uncertainties present in the geostrophic computation.

To apply salt budget considerations, let Q_i, Q_0, E, P and R represent inflow, outflow, evaporation, precipitation and runoff, respectively, each expressed as mass of water per unit time. Then conservation of water and salt can be expressed as follows:

$$\begin{aligned} Q_i &= (E - P - R)\overline{S}_0/(\overline{S}_0 - \overline{S}_i), \\ Q_0 &= (E - P - R)\overline{S}_i/(\overline{S}_0 - \overline{S}_i), \end{aligned} \tag{2}$$

where $\overline{S}_i$ and $\overline{S}_0$ are the mean salinities of the inflowing and outflowing water, defined by (1). These relationships need not be fulfilled at any given instant of time since there may be short-term variations in the total quantity of water and salt within the Gulf. The pertinent question to consider in such statements of conservation is "For how long a time can the substance under consideration accumulate (or be lost) at a reasonable rate until the concentration reaches an absurd value?" For conservation of water mass, this time is of the order of a seiche period of the gravest mode, or about a day. For salt, however, a time of the order of six months is needed for the average salinity in the upper 200 m to change measurably due to uncompensated evaporation. Therefore, all quantities in equations (2) must represent time averages of approximately six months, and we shall apply (2) not to each of the four 1957 cruises but only to their average.

Evaporation, E, can be estimated from the relationship

$$E = KA\rho W\Delta e, \tag{3}$$

where A is the surface area of the Gulf (cm^2), ρ the density of fresh water (g/cm^3), Δe the vapor pressure difference (mb) between the sea surface and the air above it, W the wind velocity (m/sec), and K a factor of proportionality, here taken as 0.011 (for details, see Sverdrup, 1951). The estimates of E, P, R in Table III are based on data collected during the cruises and on past weather data at the corresponding time of year (Servicio Meteorológico Mexicano, 1937).

These values can now be used to estimate the water exchange rate according to (2), provided that a suitable estimate of the average salinities $\overline{S}_i$ and $\overline{S}_0$ can be made. An objective way is to use the values from lines 3 and 4, derived from the geostrophic estimate. The resultant estimate of in- and out-flow is given in the last two lines of Table III for the average of the four 1957 cruises. This estimate, of course, depends rather critically on the salinity difference between the in- and out-flowing water, which, according to the geostrophic estimate, is 0.04‰. Actual examination of the salinity profiles across line 151G

TABLE III.

			February	*April*	*June*	*August*	*Average*
geostrophic estimate	Q_i	(10^{12} g/sec)	0.9	1.6	2.2	2.8	1.9
	Q_0	(10^{13} g/sec)	1.2	1.5	1.2	1.6	1.4
	S_i	(‰)	34.75	34.78	34.84	34.75	34.78
	S_0	(‰)	34.82	34.91	34.76	34.78	34.82
	E	(10^9 g/sec)	3.6	1.7	7.7	7.2	5.0
	P	(10^9 g/sec)	0.4	0.1	0.2	2.2	0.7
	R	(10^9 g/sec)	0.2	0.2	0.3	0.6	0.3
conservation of salt estimate	Q_i	(10^{13} g/sec)	—	—	—	—	3.5
	Q_0	(10^{13} g/sec)	—	—	—	—	3.5

suggests that a salinity difference 10 times greater might be more likely, and this would lead to a water exchange rate only $^1/_{10}$ as great (Roden, 1958).

It is seen that evaporation exceeds precipitation and runoff in all months examined. Precipitation amounts to less than 10% of evaporation during the first half of the year, but during the rainy season, which lasts from July to October, precipitation increases in importance. There is little runoff from the Río Colorado (Valenzuela, personal communication) and the other rivers do not discharge much water into the Gulf except during the rainy season.

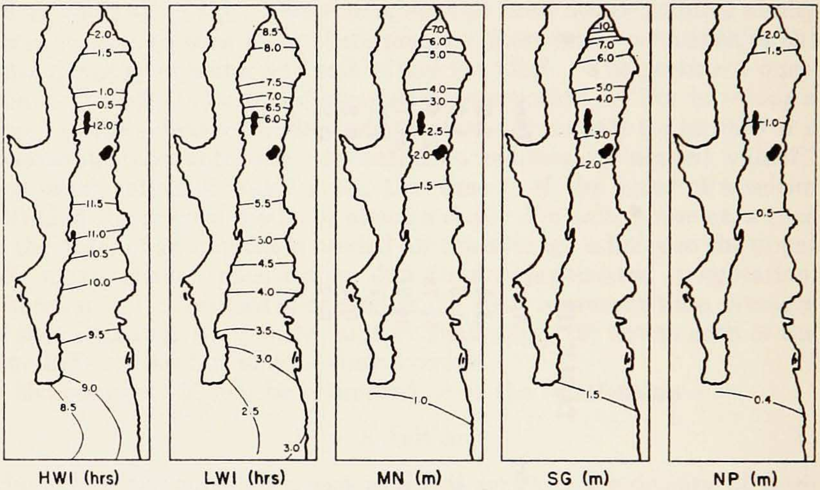

Figure 13. Tides in the Gulf of California: HWI-high water interval. LWI-low water interval. Mn mean range. Sg-spring range. Np-neap range. Time in hours; ranges in meters.

Tides. Tide observations have been recorded from very few locations in the Gulf. Generally the tide appears to be of the mixed type, with large diurnal inequalities which may predominate in some parts of the central Gulf. The composite tidal range increases gradually from the Gulf entrance to Isla Tiburón, and then rapidly toward the mouth of the Río Colorado. In this vicinity it is very large, exceeding 10 m during the spring tides. The tidal wave continues into the Rio Colorado in the form of a bore. Fig. 13 (after U. S. Coast and Geodetic Survey, 1915) shows the observed tidal ranges and high and low water intervals.

Whether the tidal oscillation within the Gulf behaves predominantly like a standing wave or like a progressive wave travelling northward depends on the amount of tidal power that is dissipated inside the Gulf.

With relatively little dissipation, most of the incoming energy would be reflected from the head of the Gulf, so that the result would appear as a standing wave. The high water interval would change rather abruptly at a node by half a tidal period. On the other hand, with relatively high dissipation, the tidal wave behaves more like a progressive wave, and we would expect the high water interval to vary smoothly with distance from the mouth of the Gulf. Evidence indicates that the time of high water gets progressively later with distance up the Gulf, with high water occurring about 5.5 hours later at its head than at its mouth; this is about the time needed for a free progressive shallow-water wave to traverse the entire length of the Gulf. But 5.5 hours is also approximately half a semidiurnal tidal period, which is the lag that would occur if the tidal wave were a pure standing oscillation. Evidence is hardly good enough to distinguish between the two alternatives.

If we neglect the small input of tidal energy by the direct action of sun and moon on the body of water in the Gulf, then the total amount of tidal power entering through the mouth is

$$P = \rho g \int h v \eta \, dx, \tag{4}$$

where h is mean water depth, η the surface elevation, v the component of orbital velocity northward along the Gulf axis, ρ the water density, and x the distance across the Gulf entrance. To get an estimate of the tidal power dissipated within the Gulf, let us assume that an ingoing progressive tidal wave is entirely dissipated. Then η and v will be in phase, and (4) gives $P = 0.4 \times 10^{18}$ ergs/sec, averaged over a tidal cycle.[2]

Let us now see if it is at all likely that such a large amount of power could be dissipated by friction of tidal currents along the bottom. The stress exerted by a tidal stream on the bottom is proportional to the square of the speed, the velocity being roughly constant from top to bottom (Taylor, 1919). The power dissipated per unit area of bottom is then proportional to the cube of the current speed, according to

$$P/A = K\,V^3, \tag{5}$$

where K is a numerical constant having a value near 0.0018. In Ballenas Trench (between Isla Angel de la Guarda and Baja Cali-

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[2] If the tidal oscillation consists of two progressive waves, one entering and one leaving, it is possible that an even greater dissipation occurs for a given tide range at the entrance provided the phase relations are such that some cancellation between the two waves occurs (Taylor, 1919).

fornia) and off the mouth of the Río Colorado, speeds of more than 3 m/sec (6 knots) have been reported (U. S. Hydrographic Office, 1951). If currents of such magnitude occurred continuously throughout a 1000 km^2 area, then it would dissipate the same amount of power, 0.4×10^{18} ergs/sec. The area required does not seem excessively large, and so the computed amount of tidal power dissipated seems reasonable. If true, the Gulf of California would supply 3% of the tidal dissipation needed to account for the observed secular acceleration of the moon.

From the free standing-wave viewpoint (no dissipation), the semidiurnal tide has a node in the central region of the Gulf, where observations show the diurnal contribution to be relatively important. The high range observed off the mouth of the Río Colorado is due to narrowing and shoaling of the Gulf.

As a result of the high tidal range and the complicated bottom topography, tidal currents are strong, especially in narrow channels and in the vicinity of Río Colorado. The mixing effected by these strong tidal currents may have important biological consequences.

Variations of Surface Slope Across the Gulf Entrance. These variations have been studied from sea level and atmospheric pressure records made in Mazatlán, Sin., and La Paz, B.C. Monthly average values of sea level for these two stations (from 1953 into 1957) are shown in Fig. 14 (A and B); a mean annual cycle, determined from three years of record, is shown in Fig. 15. It is seen that there is a prominent seasonal cycle reaching its maximum in summer and its minimum in winter, with Mazatlán leading slightly in phase over La Paz. The range of the seasonal oscillation is from 20 to 40 cm and is noticably larger in Mazatlán than in La Paz. The double maxima which are seen in three out of four annual cycles at Mazatlán may be a characteristic local phenomenon.

In the sea, the pressure gradient at the surface is composed of two parts: (1) that arising from the gradient of the surface elevation, and (2) the atmospheric pressure gradient. Note that one millibar is equivalent to approximately one centimeter of sea water pressure. The sum of the sea-surface elevation and the atmospheric pressure, expressed as equivalent height of a column of sea water, has been referred to as *corrected sea level* (Groves, 1957). The corrected sea level for Mazatlán and La Paz was computed from the monthly mean pressures at these two places (corrected to sea level) and the monthly sea level means. The difference of corrected sea level, Mazatlán minus La Paz, is shown in Figs. 14 (C) and 15 (C). This plot can be interpreted to mean the horizontal pressure difference in centimeters of sea water between the two stations. The time variations of it are proportional to variations in the inflowing geostrophic current. The datum is arbitrary, since the height of mean sea level at La Paz is unknown relative to mean sea level at Mazatlán because the two places have never been levelled in together. Consequently, the method gives only variations of the mean inflowing surface current and not the surface current itself.

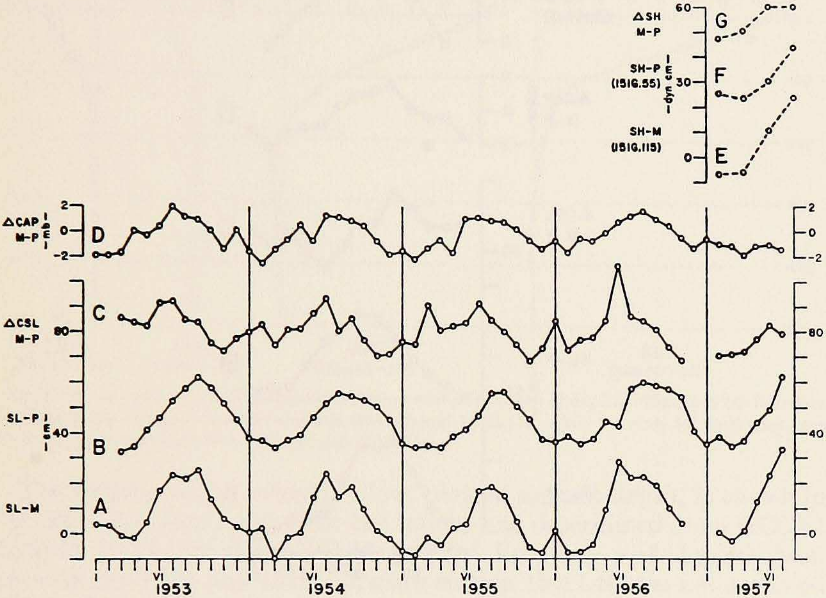

Figure 14. A—monthly mean sea level at Mazatlán; B—monthly mean sea level at La Paz; C—monthly mean difference in corrected mean sea level, Mazatlán minus La Paz; D—monthly mean difference in atmospheric pressure corrected to sea level, Mazatlán minus La Paz; E and F—steric height at stations 151G.115 and 151G.55, respectively; G—difference in steric height, station 151G.115 minus station 151G.55. Curves A, B, C, E, F, G, are plotted relative to arbitrary datum.

Mean monthly differences in atmospheric pressure (corrected to sea level), Mazatlán minus La Paz, are illustrated in Figs. 14 (D) and 15 (D). The difference is proportional to the southerly component of geostrophic wind across the entrance to the Gulf. The similarity between curves C and D in Figs. 14 and 15 might be interpreted to mean that a southerly wind across the Gulf entrance is conducive to inflow of surface waters. If it is assumed that the inflowing surface current is proportional to the surface wind from the south, the constant of proportionality can be determined by the least square method. The result is that the ratio between inflowing current and southerly wind at the sea surface is 0.0054. This value does not disagree radically with the 2% value used by navigators. The discrepancy

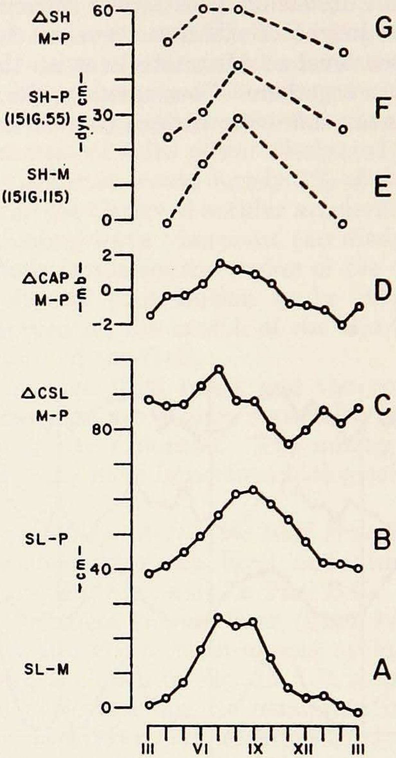

Figure 15. Curves A, B, C, D, represent an average annual cycle of the corresponding curves in figure 14. Curves E, F, G represent single observations only.

should not be taken too seriously in view of the fact that water is blown into or out of a confined basin in contrast to open ocean conditions.

Variations in *steric height* (Pattullo *et al.*, 1955) or dynamic height reflect variations in the sea surface elevation due exclusively to changes in density of sea water in a vertical column. Steric height variations across the Gulf entrance, as obtained from CCOFI stations 151G.115 (close to Mazatlán) and 151G.55 (close to La Paz), are shown in Figs. 14 (E, F) and 15 (E, F). The difference in steric height, Mazatlán minus La Paz, is shown in Figs. 14 (G) and 15 (G). Note: data for curves E, F and G represent monthly isolated instantaneous measurements, not monthly averages, and in Fig. 5 these curves are compared with other curves based on a mean annual cycle from three years of continuous data. Consequently curves A through D deserve much more confidence than do E, F, and G. In comparing curve E with A, F with B, G with C, one can say that there is no contradiction in the supposition that the observed sea level variations at Mazatlán and La Paz are related primarily to changes in density of sea water.

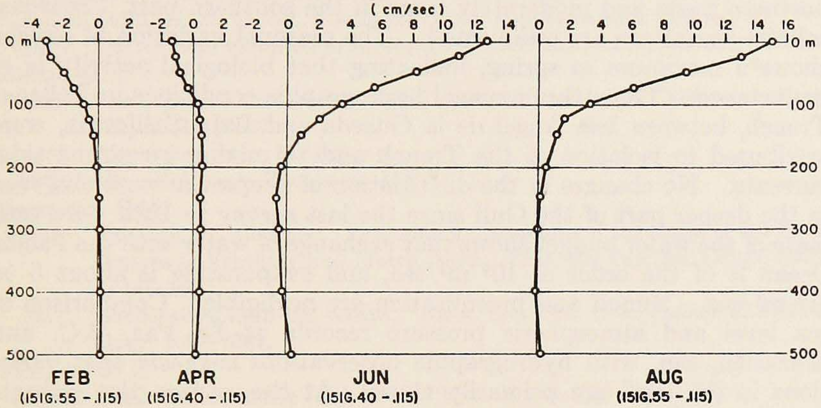

Figure 16. Horizontally averaged geostrophic current as function of depth. The plots for February and August are averaged between stations 151G.55 and 151G.115, while the plots for April and June are averaged between stations 151G.40 and 151G.115.

The horizontally averaged inflow, plotted against depth, is shown in Fig. 16. For April and June the inflow was determined from CCOFI stations 151G.115 and 151G.40 and for February and August from stations 151G.115 and 151G.55, since station 151G.40 was not occupied during the last mentioned months. It is seen that, during June and August, surface inflow is quite large and that a compensating current below 200 m is evident. February and April indicate just the opposite, with surface outflow and subsurface inflow; however, the exchange is much weaker than in summer. Exact compensation (a mean value of precisely zero, if averaged vertically) is not obtained for reasons discussed in the section on Water Balance.

In conclusion the following points seem to be borne out from observations of sea level, atmospheric pressure and density of sea water at the entrance to the Gulf of California:

(1) A southerly surface wind generates an inflowing surface current.
(2) The velocity ratio between the inflowing surface current and the southerly wind is about 0.005.
(3) Geostrophic flow at the surface is compensated by a reverse flow at depths.

Conclusions. Recent oceanographic investigations have shown that the water mass encountered in the Gulf is characteristic of Equatorial Pacific water. At the surface this water is slightly modified by extensive evaporation which increases its salinity. Seasonal temperature variations observed in the upper layers are large in the central and northern parts and moderately large in the southern part. Seasonal salinity variations are quite small. The seasonal variation of oxygen shows a maximum in spring, indicating that biological activity is of importance. The rather unusual hydrographic conditions in Ballenas Trench, between Isla Angel de la Guarda and Baja California, were attributed to isolation of the Trench and to mixing by strong tidal currents. No changes in the distribution of properties were observed in the deeper part of the Gulf since the last survey in 1939. An estimate of the water budget shows that exchange of water with the Pacific Ocean is of the order of 10^6 m^3/sec, and evaporation is about 5×10^3 m^3/sec. Runoff and precipitation are negligible. Comparison of sea level and atmospheric pressure records at La Paz, B.C. and Mazatlán, Sin. with hydrographic observations suggests that variations in sea level are primarily steric. At the surface the currents follow the winds, while at depths a compensating current opposite to the wind direction is generally indicated. The tide in the Gulf is of the mixed type with large diurnal inequalities. A large part of the tidal energy may be dissipated in the northern part of the Gulf, the tide appearing essentially as a progressive wave. The high tidal ranges in the northern part are due to narrowing and shoaling of the Gulf.

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