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Title: CURRENTS AND WATER MASSES AT THE ENTRANCE TO THE GULF OF CALIFORNIA, SPRING 1970

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Hydrographic data and drogue observations were used to describe the circulation and water masses in the upper 500 meters of the region of the entrance to the Gulf of California in the early spring of 1970.

The thermohaline structure of the water and the general circulation in the vicinity of the entrance to the Gulf of California indicated that four water masses were present. California Current water on the western side of the entrance, Subtropical Surface water in the middle part and Gulf water on the eastern side. Underlying these three waters, Subtropical Subsurface water was found from about 150 to 500 meters.

The geostrophic calculations indicate that a broad region of outflow from the Gulf existed on the eastern side associated with a marked upward displacement of isopycnals towards the east.

Speeds were near 30 cm/sec at the surface and decreased to less than 3 cm/sec at 300 meters. Outflow also occurred on the western side, near the Baja California coast, at lower speeds. Inflow to the Gulf was observed near the middle part of the entrance at speeds of 30 to 40 cm/sec at the surface, decreasing to less than 6 cm/sec at 300 meters.

The drogue observations were in agreement with the general circulation pattern inferred from geostrophic currents. Drogue and geostrophic velocities showed agreement better than 70% at 10 and 50 meters.

The decrease of geostrophic velocity with depth indicates that a baroclinic condition existed. Comparison of these velocities with the drogue measurements indicates that the baroclinic circulation was predominant in the upper 100 meters.

In the upper 150 meters the low salinity water from the California Current was flowing into the Gulf. The high salinity Gulf water was found in the regions of outflow as to be expected to avoid accumulation of salt inside the Gulf by strong evaporation.

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CURRENTS AND WATER MASSES AT THE ENTRANCE TO THE GULF OF CALIFORNIA, SPRING 1970

I. BACKGROUND STUDIES

General

The Gulf of California is an interesting natural environment in which mesoscale and microscale oceanographic processes can be studied because of the sharp contrasts in the horizontal and vertical distribution of physical and chemical properties throughout the year. These conditions are ideal not only to study the ocean from classic research vessels but also provide an adequate field to assess the reliability of remote temperature sensing techniques from satellites.

The high productivity of the Gulf of California plays an important role in the economy of Mexico. The physical process of upwelling occurs here as a result of the wind regime and the coastline configuration. This process makes nutrients available to the euphotic zone where the remarkable growth of phytoplankton brings about the abundance of commercial species that for a long time have supported the fishing industry of this region.

The stocks of some important species are decreasing and some others are changing their distribution. Overfishing decreases the abundance of valuable species but the effects of changes in the physico-chemical properties of sea water may work in both ways, that is, to increase or decrease the population. The ocean circulation is the principal mechanism that determines the distribution of properties and, in consequence, the regions of low and high productivity.

Earlier research conducted in the region of the entrance to the Gulf of California has shown the complicated oceanographic structure of this transitional zone. Its complexity is one of the principal obstacles making it difficult to adequately describe the spatial and seasonal variations of the oceanographic regime.

The circulation pattern across the mouth of the Gulf of California has attracted the attention of many authors. However, the knowledge of how the water is exchanged with the open sea is still incomplete, especially in the upper 500 meters of the entrance region where conditions vary the most.

The simple circulation scheme first proposed for the upper layers in this region assumed that outflow was taking place on the western margin of the mouth and inflow occurred on the eastern side. More recent research (Griffiths, 1965; Stevenson, 1970; Roden, 1972) proved that no such pattern persisted throughout the year. The uncertainties inherent in the indirect methods used to study the circulation may also have contributed to make results unreliable.

The origins of the water masses present over the region of the entrance to the Gulf of California are not clearly known. Recent investigations by Stevenson (1970) and Warsh (1973) pointed out that surface water from the eastern tropical Pacific reaches the vicinity of the Gulf's entrance. This fact was not considered in earlier research.

For the purpose of this study, the "mouth" of the Gulf of California is defined as being a line from the southern end of the Baja California peninsula to Sinaloa on the mainland, at about 24^{o} latitude North (Figure 1). The "region of the entrance" will mean the region north of the mouth, to an arbitrary line between La Paz and Topolobampo. These definitions are different from what Hubbs and Roden (1964) considered to be the oceanographic boundary of the Gulf (a line from Cabo San Lucas to Cabo Corrientes).

In the early spring of 1970, two research vessels were sampling the region of the entrance to the Gulf. Within five days 43 hydrographic stations were occupied and the first direct observations of currents were made by tracking parachute drogues. These data were considered useful for studying the geostrophic circulation in a three dimensional pattern and comparing these results with direct measurements of currents. The observed circulation in early spring can also be compared with the occurrence of the different water masses in the upper 500 meters at that time.

The geostrophic computations, drogue observations and their relation to the water masses in the spring of 1970 are the subject of this thesis.

Description of the Water Masses

Sverdrup (1941) was the first to discuss the nature of the water masses present in the Gulf of California and the water exchange between this elongated basin and the Pacific Ocean. His attempts to describe the circulation by means of density distribution were not successful because of its complexity. However, he was able to determine that the deep water of the Gulf was similar to that of the equatorial Pacific.

Roden (1958) and Roden and Groves (1959) summarized the oceanographic research available until 1957 and by further analysis of these data they suggested that the Gulf of California could be divided into three regions: the northern, the central and the southern (Figure 1).

The northern part, between Río Colorado and Isla Tiburón near 29^{o} north, is a small basin with depths shallower than 200 meters except near Baja California where a narrow trench reaches 1,000 meters. Of the three regions, it is affected the most by the arid climate and the surrounding land. Precipitation and runoff are negligible and there is strong heating and evaporation. Surface and deep water temperatures during winter are 14 ^{o}C and 11 ^{o}C, respectively; in the summer they reach 30 ^{o}C and 16 ^{o}C. Salinity is above 35.2 $^{o}/oo$ with very little variation throughout the year.

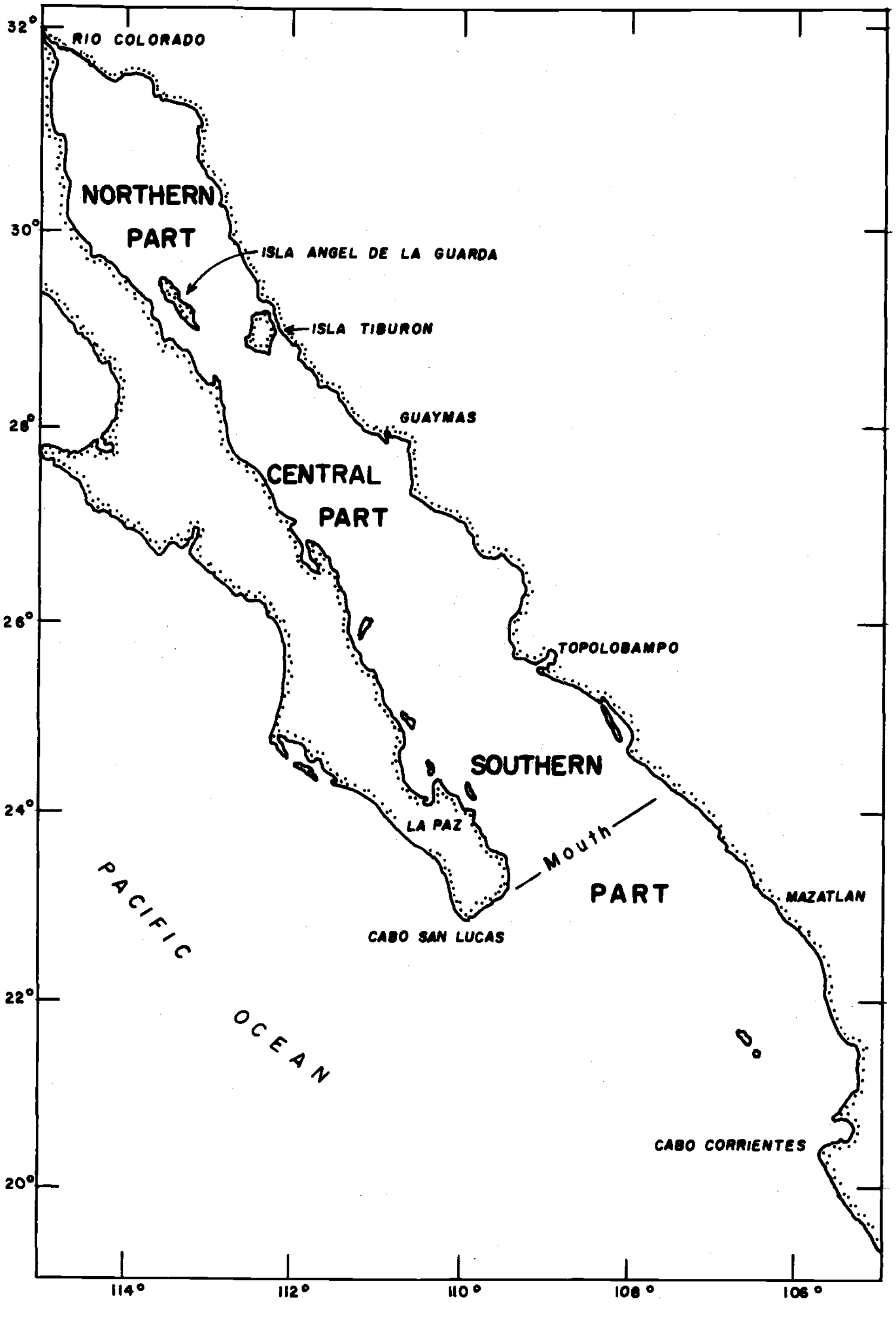


Figure 1. Location of the Gulf of California and its oceanographic regions (after Roden and Groves, 1959).

However, in some locations it may be as high as 35.8 ^{o}/oo especially in enclosed bays and lagoons.

The central part, between Isla Tiburón and Topolobampo at 25^{o} north, is separated from the northern part below 200 meters by a submarine ridge except between Isla Angel de la Guarda and the Baja California coast where a deep and narrow trench runs parallel to the coast with depths greater than 800 meters. Open communication with the ocean exists down to 1, 500 meters on the south. In this region, Pacific equatorial water has been strongly modified by evaporation and heating above the thermocline (50 to 100 meters) producing a different mass of water that is referred to by Roden as Gulf water. This water has high salinities (above 35.0 ^{o}/oo) similar to those of the northern part. Below the thermocline Pacific equatorial water can be identified by a salinity minimum near 34.5 ^{o}/oo, between 600 and 800 meters and an oxygen minimum of 0.1 to 0.2 ml/1, between 400 and 800 meters.

The southern part, between Topolobampo and Cabo Corrientes, communicates with the open ocean down to 3, 000 meters. It has a complicated distribution of properties above 300 meters. The presence of water from the California Current is evident south of Cabo San Lucas at depths near 100 meters. The interaction of California Current water having low temperature and salinity with Gulf water having high temperature and salinity and the Pacific equatorial water having high temperature and relatively low salinity produces a complicated distribution of these properties (Griffiths, 1965).

Wyrtki (1967) described the water masses in the eastern equatorial Pacific Ocean, between the Baja California peninsula in the north (24° north) to Peru in the south (10° south). In the upper 500 meters these waters are: Tropical Surface water having high temperature and low salinity. Subtropical Surface water of warm but variable temperature and high salinity, California Current water of low temperature and low salinity, and Subtropical Subsurface water with high salinity as a shallow salinity maximum.

According to Wyrtki (1967) the Gulf of California is influenced by California Current water and Subtropical Surface water above roughly 200 meters. The water having high salinity (above 35.0 °/oo) that is formed inside the Gulf is included in the Subtropical Surface water.

Griffiths (1968) described the kinds of waters near the mouth of the Gulf of California in the spring of 1960 using the classification proposed by Wyrtki (1967) and compared this classification with that given by Roden and Groves (1959) in which California Current water, Gulf water and Equatorial water are considered. Griffiths found that above 700 meters Subtropical Subsurface water was present as a salinity maximum of 34.8 °/oo at 200 meters. The waters at the surface were: California Current water south of Cabo San Lucas, Gulf water near the east coast and Subtropical Surface water further south. In a transect at the mouth of the Gulf Griffiths reported that Gulf water was present over the entire transect from the surface to 100 meters near Baja California and to 30 meters near the coast of Sinaloa. In the spring of 1960 California Current water was not detected at the mouth.

The results of eight cruises distributed throughout the year, with data for the upper 250 meters, were discussed by Stevenson (1970). The water masses identified south of the mouth of the Gulf were reported in terms of the classification proposed by Roden and Groves (1959). California Current water persisted near Cabo San Lucas all the year from the surface to 100 meters or even 150 meters. Gulf water was detected flowing out of the Gulf as a thin surface layer during January, April and June. This water of high salinity (above 34.9 $^{o}/oo$) was advected intermittently out of the Gulf in limited amounts.

Using data from two transects in the region of the entrance to the Gulf, during summer, Warsh (1973) redefined the upper water masses in this region as Transition water A, Transition water B, Gulf water and Gulf Surface water in the following way:

water mass	depth	Sal. $^o/oo$	
Transition water A	30-50 m	<34.6	-Mixture of surface waters of the California Current and Tropical Surface water.
Transition water B	50-200	34.6-34.9	-Mixture of Subsurface waters of the California Current and Subtropical Subsurface water.
Gulf water	125	>34.9	-Water formed inside the Gulf by heating and evaporation.
Gulf Surface water	0-30	< 34.6	-Mixture of surface waters from the California Current and Tropical Surface water.

The temperature of the waters described above is always greater than 13^o C. This classification was based on physical-chemical properties, especially silicate-salinity and phosphate-salinity relationships.

Meteorology of the Region

Roden (1958), Roden and Groves (1959) and Hubbs and Roden (1964) have described the winds in the region of the Gulf of California. During winter and spring the winds are from the northwest with predominant speeds near 5 m/sec; during summer and fall the winds blow from the southeast over the central and southern parts of the Gulf at about 3 m/sec.

Currents

The surface circulation is predominantly wind driven according to Roden (1958). It follows the wind at the surface while compensating currents exist at lower levels.

Theoretical studies of the surface currents were done by Roden (1964) using a linear and stationary model. He considered the effects of a geostrophic part, a component due to the horizontal atmospheric pressure gradient and a component produced by the wind stress. The following results were obtained for the central part of the Gulf, near Guaymas.

Component	Speed in cm/sec Feb.	Aug.
Geostrophic	- 4	13
Horizontal gradient of atmospheric pressure	- 1	2
Vertical gradient of the horizontal wind stress	- 5	6
Resultant	-10	21

Negative speeds indicate currents to the south, going out of the Gulf, and positive speeds indicate currents to the north.

Hubbs and Roden (1964) and Wyrtki (1965) gave monthly averages of the surface currents just south of the mouth as computed from shift drift records. Southerly currents predominated in winter and spring, becoming westerly during summer and fall. Speed averaged 10 cm/sec with maximum near 15 cm/sec. It was also observed that the California Current has a stronger southerly componement during spring near the southern end of Baja California.

The horizontal distribution of geostrophic currents south of the mouth of the Gulf at the surface and 125 meters were described by Griffiths (1968). The data were collected during April and May and the currents were referenced to 500 and 1, 000 meters. GEK and geostrophic estimates showed slow meandering currents in opposite directions alternately across the mouth, with speeds from 10 to 40 cm/sec.

Further information on geostrophic currents referenced to 250 meters in the region just south of the mouth have been given by Stevenson (1970). Southward currents with speeds of 20 cm/sec were observed at the surface from January through April, decreasing in magnitude by June and becoming northerly in August. Similar directions but lower speeds were observed at 100 meters. During January the outflow across the mouth took place above 100 meters at 5 to 10 cm/sec. Also during this month the California Current was detected turning around Cabo San Lucas and going into the Gulf.

Warsh and Warsh (1971), dealing with the discrepancies in the water balance by geostrophic computations, obtained a reference level that changes across the mouth. The two bases for choosing this reference level were: (1) the best agreement exists between inflow and outflow and (2) the high salinity water flows out of the Gulf on the western side of the mouth.

The most recent and detailed description of baroclinic flow across the mouth has been given by Roden (1972) for December of 1969. A transect of closely spaced stations, nine kilometers apart, showed a well defined pattern of high speed cores down to 600 meters. The regions of outflow occurred at both sides of the mouth with inflow in the middle part. Speeds from 40 to 50 cm/sec were common. The reference level was taken at 1, 500 meters.

Water Exchange: Gulf of California-Pacific Ocean

The first computations of water exchange between the Gulf of California and the Pacific Ocean were made by Roden (1958) with data for February and March. The equations of conservation of salt and water gave an inflow Q_i of 1. 19 Sverdrups (1 Sverdrup = 1 Sv = 10^6 m^3/sec) occurring in the upper 50 meters and an outflow Q_o of 1. 17 Sverdrups taking place above 1, 500 meters. Since the two figures are nearly equal, it was assumed that evaporation has a negligible effect on the circulation.

With more available information Roden and Groves (1959) obtained water transport across the mouth above 500 meters by means of salt balance and geostrophic computations. The salt balance gave an estimated Q_i and Q_o near 3.5 Sv as an average over six months. The geostrophic estimates for Q_i and Q_o were 1.9 and 1.4, respectively, being averages over about a day. The discrepancies between inflow and outflow were ascribed to: (1) the lack of information of the flow below 500 meters; (2) the reference level at 500 meters was not adequate; (3) the presence of ageostrophic currents; and, (4) the mouth was not completely spanned by the end stations of the transects.

Roden (1972) computed the baroclinic transport relative to 1,500 meters based on 34 STD stations across the mouth of the Gulf in December. He obtained an inflow Q_i of 10 Sv and an outflow Q_o of 12 Sv. The observed difference was thought to be compensated by inflow taking place below 1,500 meters at speeds lower than 1 cm/sec.

One common feature of the circulation across the mouth of the Gulf is a narrow high speed core of high salinity water (above 35.0 $^o/oo$) flowing out along the coast of Baja California at depths near 50 meters. This water seems to have originated in the northern part of the Gulf as shown by the tongues of high salinity water along the coast of Baja California (Roden and Groves, 1959; Roden, 1964; Hubbs and Roden, 1964; Warsh and Warsh, 1971). In the detailed study of the thermohaline structure at the mouth of the Gulf, Roden (1972) also observed the high speed core on the western side of the mouth but it extended from the surface to about 1, 000 meters, an outstanding feature not described previously.

Conclusions

The previous information about the Gulf of California indicates that the region of the entrance undergoes extreme variations in its oceanographic regime. Three points are of interest for the present study: (1) The sources of water at the region of the entrance have been reported and, in general, the authors agree about their origins (except for the new evidence given by Stevenson (1970) and Warsh (1973) that Tropical Surface water reaches the region of the entrance to the Gulf during summer); (2) the transports Q_i and Q_o across the mouth in the upper 500 meters are roughly 2 Sv $\pm$ 1 Sv; and (3) strong baroclinic currents have been found in this region. (Unfortunately there are no direct measurements of the total current simultaneous to the determination of the relative field of pressure to compare the circulation obtained by both methods.)

Objectives of this Thesis

On the basis of the three general points mentioned before the analysis of the data described in the next section will be oriented to two principal objectives:

(1) To study the water masses and geostrophic circulation in the region of the entrance to the Gulf of California as observed in the spring of 1970 and compare the results with previous works.

(2) To study the currents in the upper 500 meters comparing the results of two different methods; the geostrophic assumption and direct measurements.

II. OBSERVATIONAL PROGRAM

The Projects

The research vessel CAYUSE from Oregon State University was sent to the Gulf of California as the first direct effort of this institution to study the physical and chemical properties, the circulation and primary production during the early spring of 1970. At this time of the year the Gulf shows interesting oceanographic features like upwelling along the eastern margin with remarkable phytoplankton blooms. Also at this time of the year the California Current has its maximum southward extension off the Mexican coast, near the entrance to the Gulf.

The research vessel DAVID STARR JORDAN from the National Marine Fisheries Service was working at the same time in the region of the entrance to the Gulf in an inter-agency study with the participation of scientists from the United States and Mexico. The study was part of the project "Little Window" directed to evaluate the resolution of the infrared surface temperature sensors aboard the NASA and NOAA satellites (Stevenson 1971).

The Cruises

The CAYUSE made the first drogue station (drogue station 1) on March 18 near the eastern side of the Gulf (Figure 2) and proceeded to make nine hydrographic stations across the Gulf. Seven of these stations were included in transect II. On March 23 the drogue station 2 was occupied on the western side, off La Paz. The CAYUSE continued north to the central and northern parts of the Gulf and returned to the site of transect II on April 3 to occupy the drogue station 3 at the middle of this transect. Seven additional hydrographic stations were made in the vicinity of this drogue station but these were not included in transect II.

On March 18 the JORDAN made the first nine hydrographic stations in this region. On March 20 seven stations were occupied along a line across the Gulf, from La Paz to Topolobampo (Transect III, Figure 2). During the next three days the JORDAN sampled six other hydrographic stations in the same area and then went south to the mouth of the Gulf and sampled 12 stations on March 23 (Transect I).

Measurements

The stations made by the CAYUSE consisted of hydrographic casts to a depth of 1,000 meters in the middle of the Gulf and shallower near the coast. The temperature was read from reversing thermometers with a reported accuracy of $\pm$ 0.02 ^{o}C. The salinity was measured on board using an Australian induction salinometer with precision of $\pm$ 0.004 $^{o}/oo$ (Wyatt, et al., 1971).

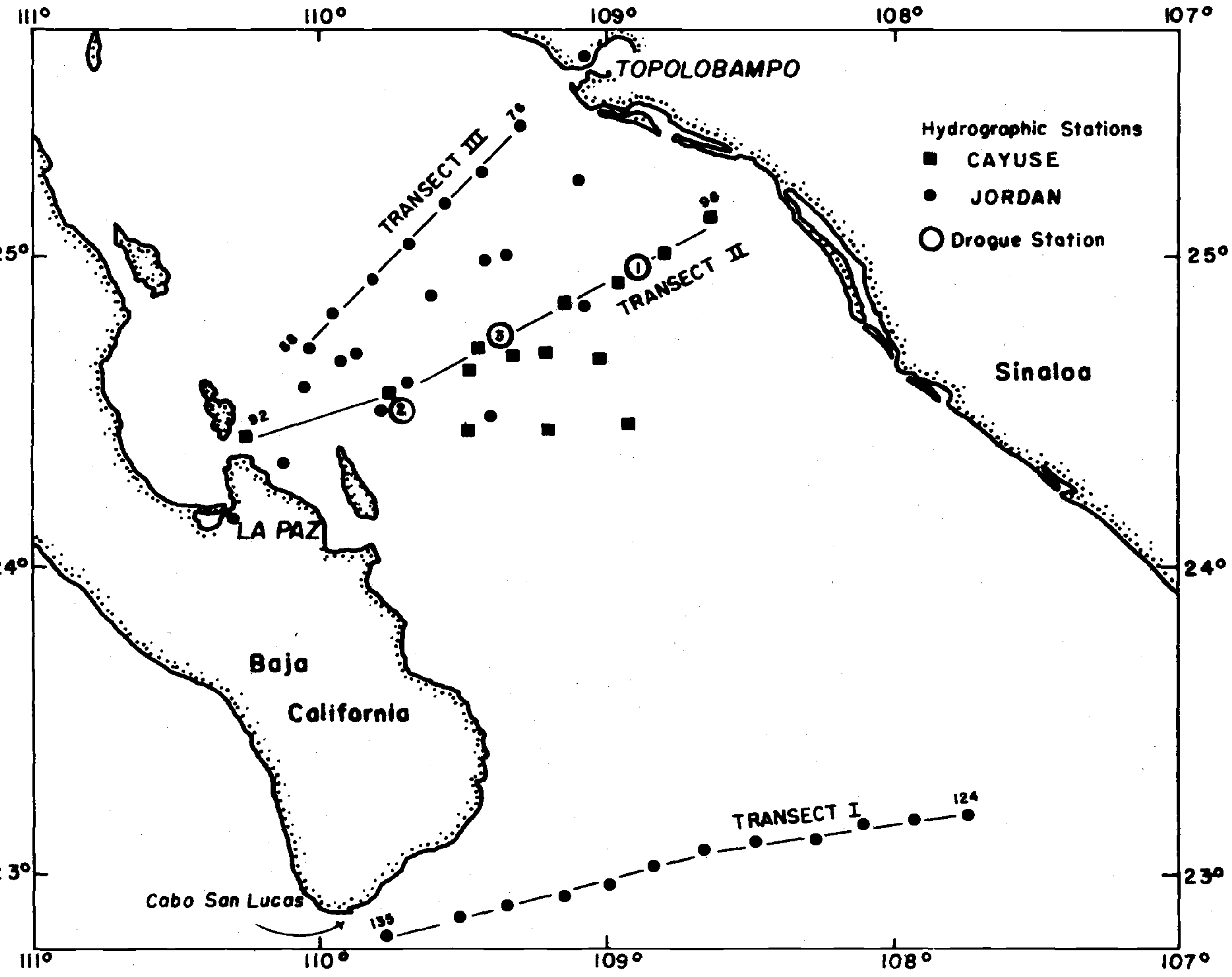


Figure 2. Stations made in the region of the entrance to the Gulf of California in March and April of 1970.

The hydrographic stations occupied by the JORDAN consisted of temperature, salinity and depth measurements with a Bissett-Berman Model 9006 STD system that gave an accuracy of $\pm$ 0.02 ^{o}C for temperature and $\pm$ 0.01 ^{o}/oo for salinity. Calibration Nansen casts were made at the beginning and at the end of the cruise (Stevenson, 1971). Station data along transects are summarized in Table 1.

Table 1. Summary of station data along transects. Gulf of California, spring 1970.

Transect	Date	Ship	Measurements	Stations	Duration
I	Mar 23	JORDAN	STD: temperature and salinity	124-135	16 hrs.
II	Mar 22	CAYUSE	Hydrocasts: temperature, salinity, 0_2, nutrients, pH, chlorophyll	92-98	29 hrs.
III	Mar 20	JORDAN	STD: temperature and salinity	76-88	9 hrs.

Observation of the sea state and weather were made at each station by both research vessels. The wind velocity was measured with on-board instruments.

The CAYUSE made the direct observations of currents by means of parachute drogues at three locations in transect II (Figure 2). One drogue was set at each of four depths: 7, 50, 110, and 250 meters. These drogues were tracked for 18 to 26 hours and were similar to those utilized by Stevenson, et al., (1969), described previously by Volkman, et al. (1956). The drogues consisted of a parachute eight meters in diameter attached to a surface float by means of a propylene rope of length equal to the depth of measurement.

The drogue positions relative to the ship were recorded every 15 minutes by radar fixes. At the same time the position of the ship was referred to an anchored buoy. The wind velocity was registered every 15 minutes during the time when the drogues were tracked. Uncertainty in radar fixes has been estimated as ± 0.02 km and ± 0.25 degrees (Stevenson, 1969).

Treatment of Data

STD analog data were manually digitized and computer processed by the Inter-American Tropical Tuna Commission at La Jolla, California. The computer program yielded values for temperature and salinity at 0, 10, 20, 30, 50, 75, 100, 125, 150, 200, 300, 400, and 500 meters. Computer values of σ_t, thermosteric anomaly, dynamic height and stability were also given at the same depths (Stevenson, 1971).

The data collected by the CAYUSE were processed at Oregon State University. Interpolated values of temperature and salinity were calculated for all the depths listed above except 125 meters.

At these same depths computed values of σ_t, thermosteric anomaly and dynamic height were also given at the same depths (Wyatt, et al., 1971).

Geostrophic currents at different depths across transects I, II and III were calculated by a computer program. These unpublished calculations were made by Dr. Merrit Stevenson of the Inter-American Tropical Tuna Commission at La Jolla, California, who made them available for the purpose of this thesis.

The drogue observations were computer processed using the programs described by Stevenson (1966) and Wyatt, et al., (1967) to determine the mean speed of the drogues, the dominant periodicities and oscillations of the motion as follows:

First, the drogue positions after successive time intervals of 15 minutes were referred to a cartesian coordinate system using the x and y positional values. Regression lines were fitted by least squares using each one of the two components, the time being the independent variable in both cases. A normalized series for the x values was obtained by subtracting the regression line from each observed x value (deviations from the regression line). The same treatment was applied to the y values. The two normalized series have a zero mean.

Further analysis involved the autocorrelation method to obtain the dominant period of the drogue motion (that with the largest amplitude) if such a period was present in the observations. The method uses the zero-mean normalized series. The autocorrelation technique was introduced by Fuhrich, cited by Conrad and Pollack (1950) and has been applied to ocean current measurements by Stevenson (1966) and Stevenson, Patullo and Wyatt (1969) off the Oregon coast. The advantage of this method is that it may be applied to time series of limited length. Only one and a half or two times the length of the dominant period will be sufficient. A brief description follows, taken mostly from the text by Conrad and Pollack (1950) and Stevenson (1966).

Let the terms in the normalized series be

$$Y_1, Y_2, Y_3, Y_4, \ldots, Y_n$$

such that
$$\sum_{i=1}^{N} Y_i = 0$$

Let Y'_1 be the correlation coefficient between the subsets

$$Y_1, Y_2, Y_3, \ldots, Y_{N-1} \text{ and } Y_2, Y_3, Y_4, \ldots, Y_N$$

let Y'_2 be the correlation coefficient between the subsets

$$Y_1, Y_2, Y_3, \ldots, Y_{N-2} \text{ and } Y_3, Y_4, Y_5, \ldots, Y_N$$

In a similar way we may use the subsequent subsets to obtain the correlation coefficients up to $Y'_{N'}$. The set of correlation coefficients (actually called autocorrelation coefficients)

$$Y'_1, Y'_2, Y'_3, Y'_4, \ldots, Y'_{N'}$$

is called the first transformed series. If this first transformed series is used as the original normalized series, a new transformation will yield the second transformed series and with a similar procedure we can construct the n^{th} transformed series. A plot of the autocorrelation coefficients of a transformed series versus time is the correlogram of that transformed series.

The original normalized series includes periodic and random fluctuations. After a number of transformations the random fluctuations are almost eliminated and the correlogram will approach a sinusoidal pattern. The period of this curve will be equal to the dominant period of the normalized series. This period can be used as an input to calculate the amplitude of oscillation by means of Fourier analysis.

Two important disadvantages of this method are: (1) the calculations are extensive and require adequate computer facilities and (2) there is no rigorous method to estimate the reliability of the computed period. To overcome the second disadvantage Fuhrich defined the parameter ρ as the dispersion of the transformed series

$$\rho = \frac{1}{2\sigma_1^2}$$

where σ_1^2 is the variance of the first transformed series. The variance of a pure cosine curve is

$$\sigma^2 = 1/2$$

so that for a perfect sinusoidal variation $\rho = 1$.

Values of ρ close to 1.0 indicate a reliable estimate of the dominant period. Conrad and Pollak and Stevenson have considered that the computed period is reliable if the ρ values are between 1.0 and 1.3 and for ρ values from 1.3 to 1.8, the period is probably real. For series that are mostly random fluctuations, ρ may be of the order of N/2, where N is the number of terms in the series.

III. DISTRIBUTION OF PROPERTIES

Distribution of Properties: Salinity

Salinity has been found to be a good indicator of the different kinds of water in the Gulf of California (Griffiths, 1963). Therefore, sections of vertical salinity distribution were constructed from the three transects across the region of the entrance to the Gulf.

The vertical distribution of salinity for transects I, II, and III are shown in Figure 3a, b, c. A plot of temperature versus salinity for the three transects is given in Figure 4.

From 150 to 400 meters the water has salinities between 34.6 ^{o}/oo and 34.8 ^{o}/oo with a temperature range from 8.5 ^{o}C to 13.0 ^{o}C in the three transects. Above 150 meters the salinity values fall both above and below the range just mentioned defining regions of relatively low salinity (from 34.0 ^{o}/oo to 34.6 ^{o}/oo) and regions of relatively high salinity (from 34.9 ^{o}/oo to 35.3 ^{o}/oo). The temperature-salinity diagram of Figure 4 indicates that the high and low salinity water have temperatures from 13 ^{o}C to 21 ^{o}C. The water with intermediate salinity (from 34.6 ^{o}/oo to 34.9 ^{o}/oo) shows the entire range of temperatures in the upper 400 meters (8.5 ^{o}C to 23.0 ^{o}C).

From 400 to 500 meters the salinity decreases to values near

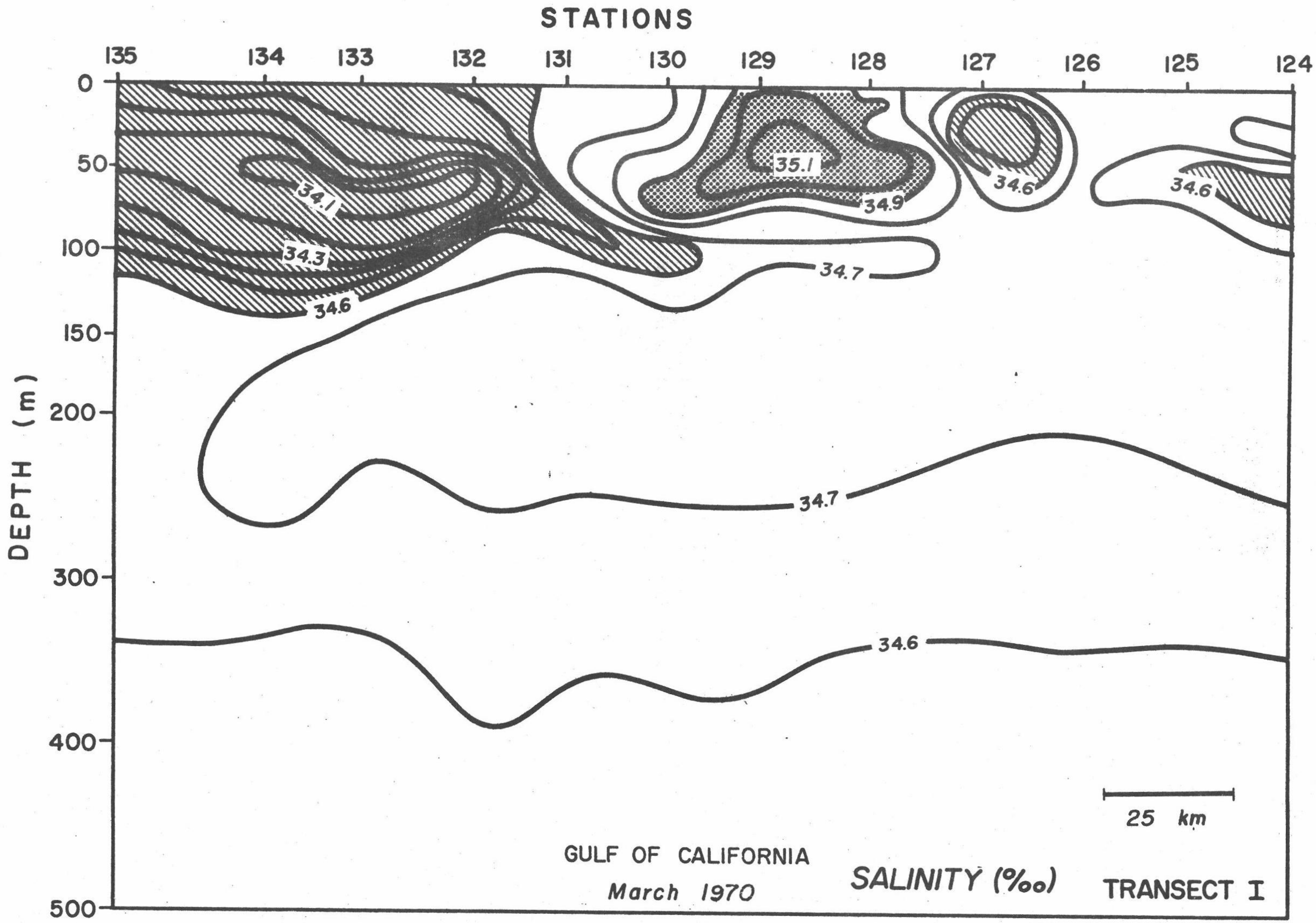


Figure 3a. Vertical distribution of salinity in transect I. Contour interval: 0.1 ‰. Lined areas are low salinities. Dotted areas are high salinities.

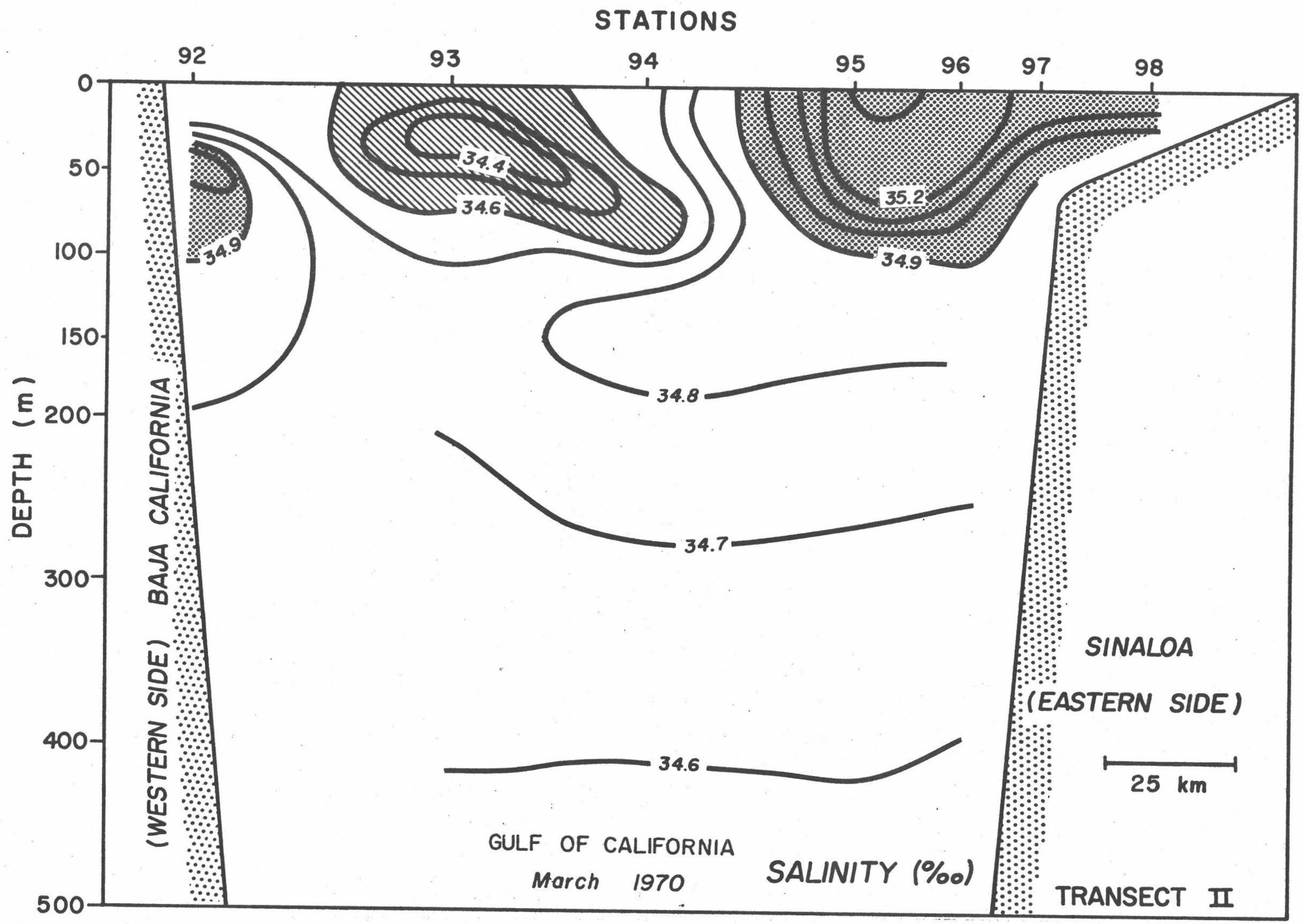


Figure 3b. Vertical distribution of salinity in transect II. Contour interval: 0.1 $^{o}/oo$. Lined areas are low salinities. Dotted areas are high salinities.

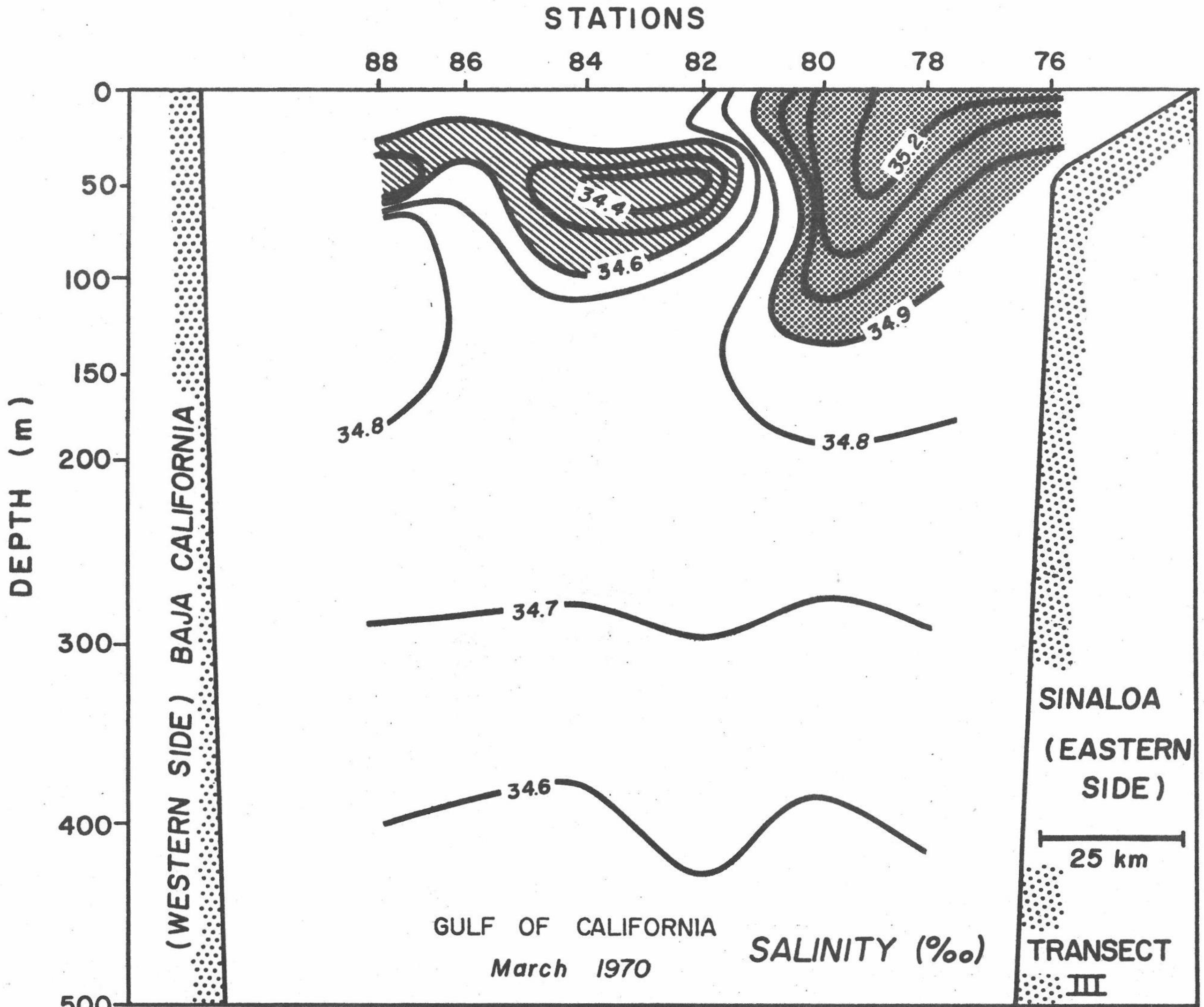


Figure 3c. Vertical distribution of salinity in transect III. Contour interval: 0.1 ^{o}/oo. Lined areas are low salinities. Dotted areas are high salinities.

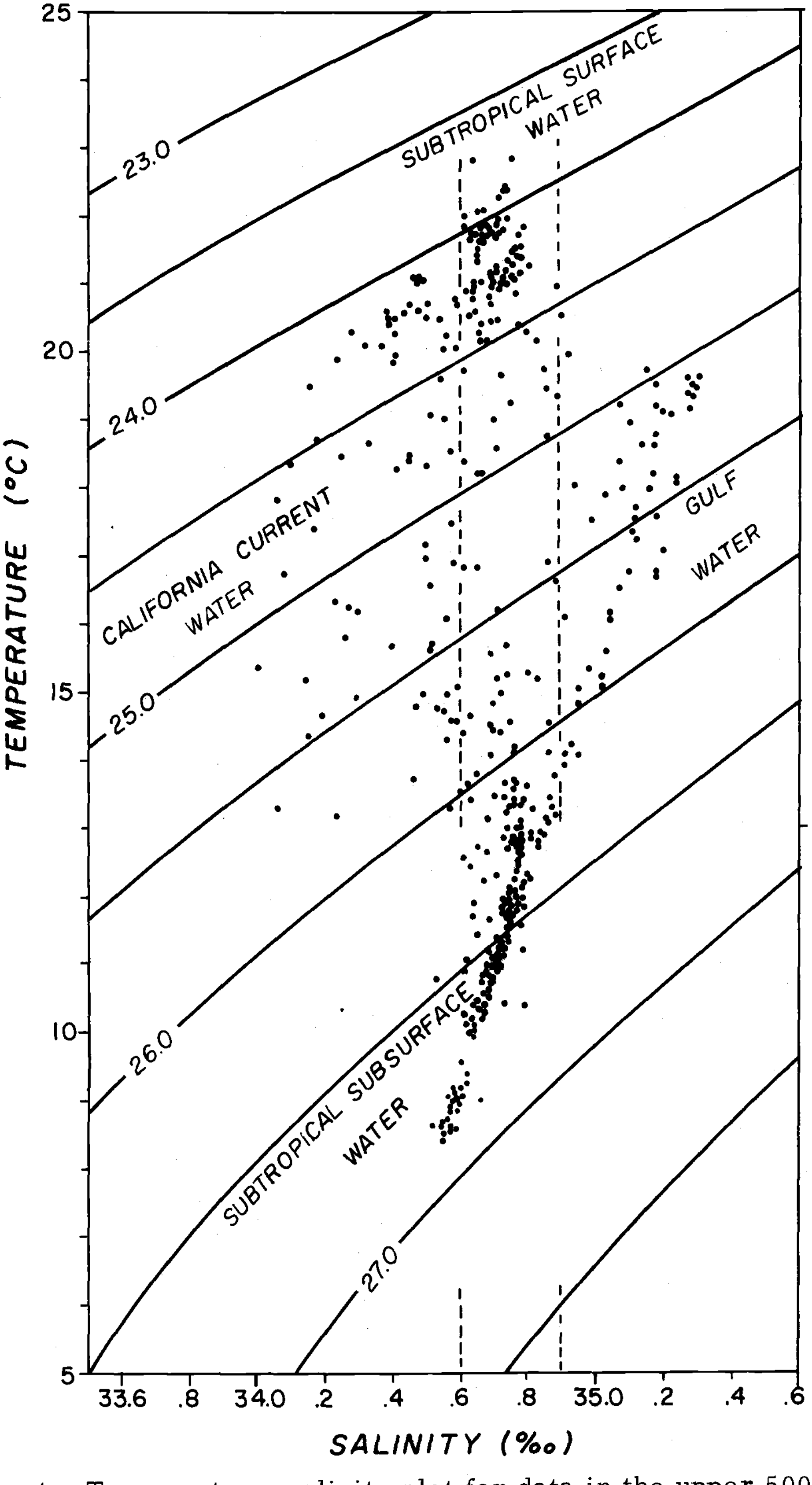


Figure 4. Temperature-salinity plot for data in the upper 500 meters in transects I, II and III. Gulf of California, spring of 1970.

34.5 $^{o}/oo$ and the temperature decreases to 7.5 ^{o}C.

The regions of low and high salinity can be detected in the three transects as surface or subsurface cores. Strong vertical salinity gradients are present above 150 meters reaching 0.4 $^{o}/oo$ in 20 meters as in transect I at station 132, between 50 and 100 meters. Horizontal gradients can not be evaluated adequately because the sampling scale is too large.

The low salinity water is present from the surface to 150 meters on the western side of transect I, between stations 130 and 135. A small core of low salinity can be seen at station 127 centered at 25 meters. The amount of low salinity water, as inferred from the area inside the 34.6 $^{o}/oo$ isohaline, decreases towards the northwest (interior of the Gulf). In the northernmost transect (transect III) this low salinity water exists as a subsurface core centered between 50 and 75 meters in the middle part of the transect.

The high salinity water, bounded by the 34.9 $^{o}/oo$ isohaline occurs on the eastern side of the Gulf as a surface core in the upper 150 meters in transect III and above 100 meters in transect II. The same core appears to be present in transect I to the south, centered between 30 and 50 meters at station 129. A tendency in the amount of this high salinity water to decrease in the southward direction is observed in the three transects. In all cases the high salinity water overrides to some extent the low salinity water. There is an indication of another core of high salinity water on the western side of transect II, at station 92. This core is not evident in the transect III to the north, but no stations were made close to the Baja California coast. There is no evidence of this core in transect I although stations were occupied near the coast.

Distribution of Properties: Temperature

Temperature cross sections are shown in Figures 5a, b, c. In the three transects the upper mixed layer shows little change in temperature (20 °C to 21°C). The surface maximum of 21.6 °C occurs on the eastern side of transect I. The thickness of the mixed layer varies from 10 to 50 meters. The thermocline, bounded by the 15 °C and 20 °C isotherms is about 50 meters thick. Below this region of rapid change the temperature decreases steadily to less than 8 °C at 500 meters. The isotherms in the region of the thermocline are displaced upwards on the eastern side of transects II and III. This displacement is better developed in transect II where the 18 °C isotherm intersects the sea surface. At station 97 the temperatures are 3 °C lower than those to the west of station 95. The 20 °C, 18 °C, 16 °C and 14 °C isotherms also bend upwards near station 93 but do not reach the surface. In transect I isotherms rise near station 129 where the minimum surface temperature of 19.9 °C was measured.

Distribution of Properties: Density

The vertical distributions of density (σ_t) for the three transects are given in Figures 6a, b, c. The isopycnals show features similar to those of the isotherms. The pycnocline, bounded by the 24.5 and 26.0 σ_t isopycnals, is a layer nearly 75 meters thick with its top at 30 to 50 meters on the western side of the transects. On the eastern side, the pycnocline rises and intersects the sea surface east of station 94 in transect II and east of station 92 in transect III. In transect I the pycnocline rises and the 24.5 σ_t isopycnal reaches the surface at station 129.

Wind

North to northwesterly winds prevailed during March and April of 1970 in the region of the entrance to the Gulf of California. Winds were predominantly from the north from March 12 to 15. Between March 15 and 18 winds were variable at speeds from 3 to 5 m/sec. From the 18th of March to April 5th winds from the north and north-west were set over the region under study with speeds between 6 and 9 m/sec. The wind field, as obtained from the ship observations, is illustrated in Figure 7, after Stevenson (1971).

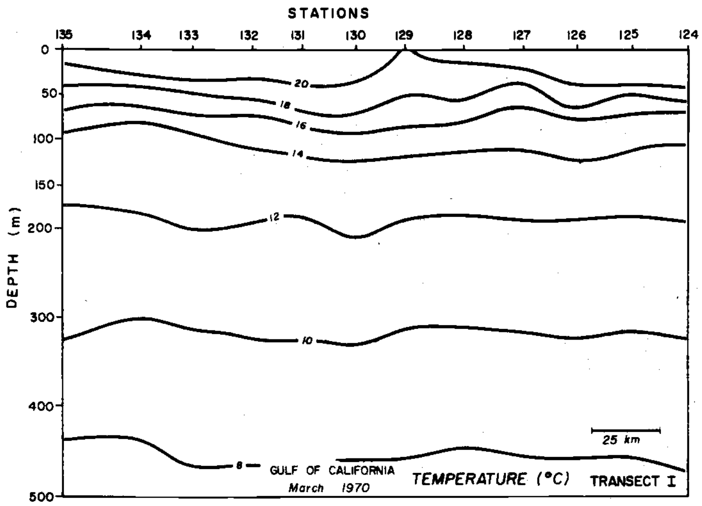


Figure 5a. Vertical distribution of temperature in transect I.

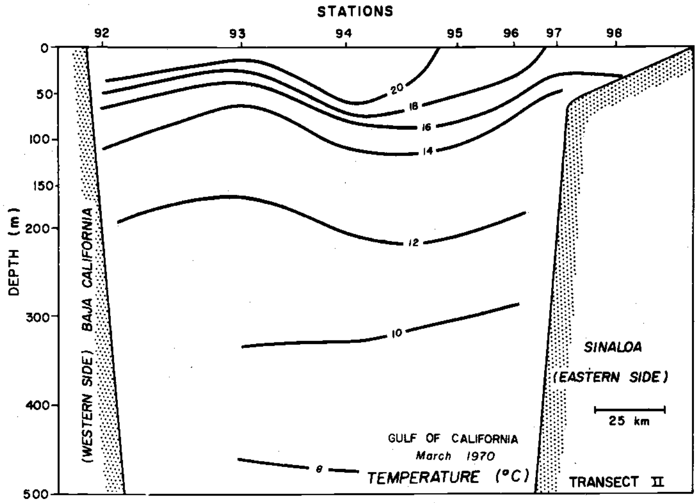


Figure 5b. Vertical distribution of temperature in transect II.

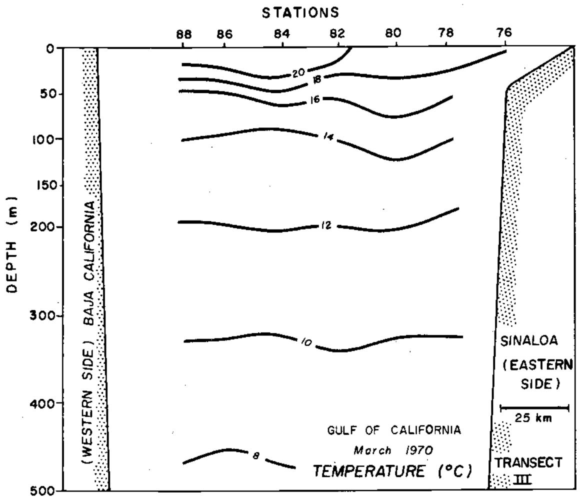


Figure 5c. Vertical distribution of temperature in transect III.

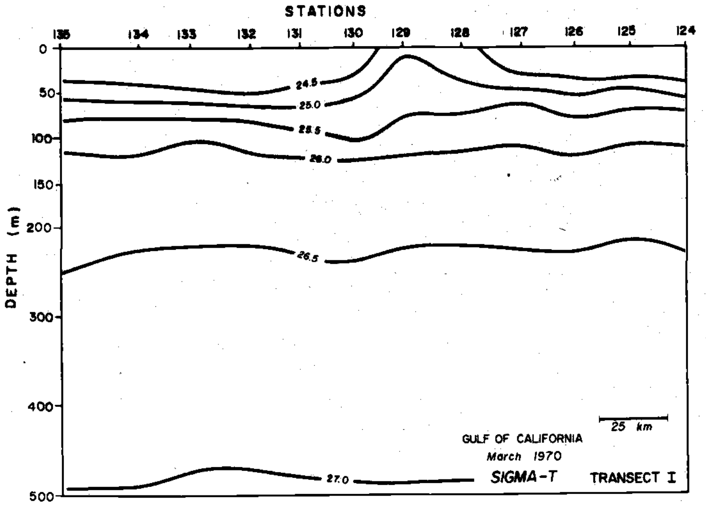


Figure 6a. Vertical distribution of density (sigma-t) in transect I.

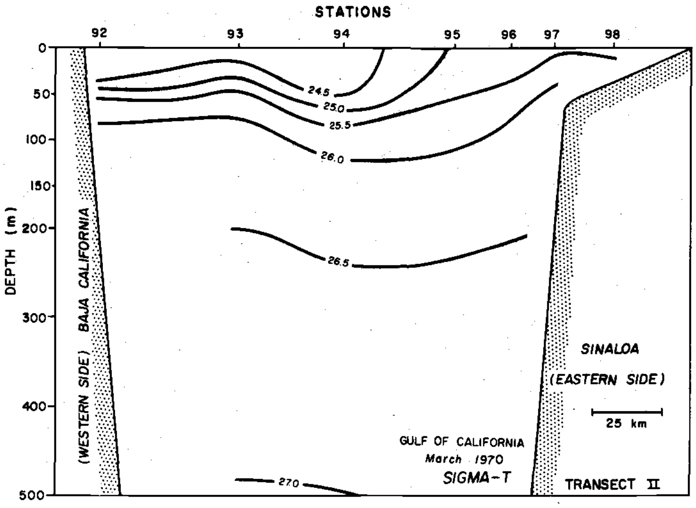


Figure 6b. Vertical distribution of density (sigma-t) in transect II.

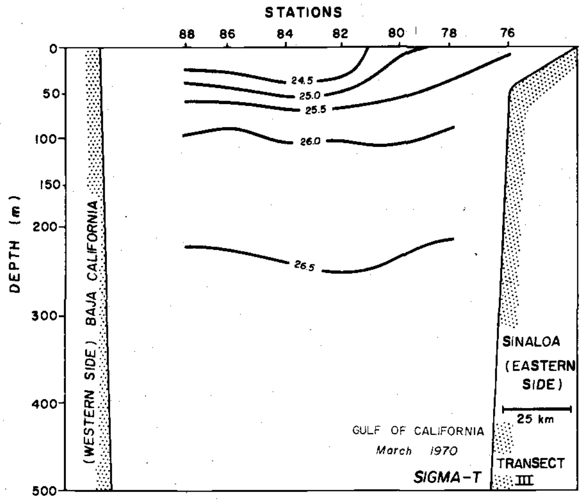


Figure 6c. Vertical distribution of density (sigma-t) in transect III.

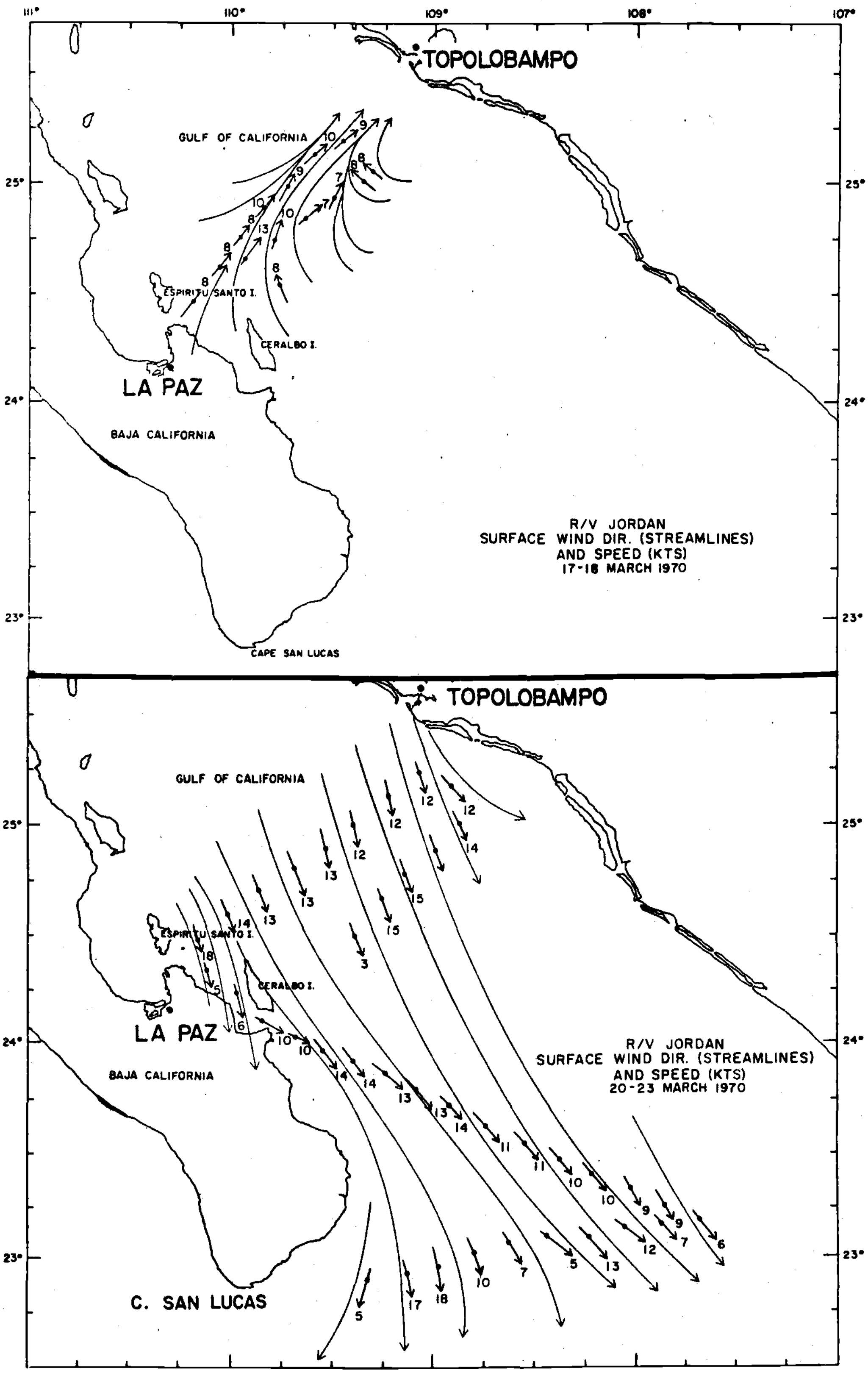


Figure 7. Observed winds at the entrance to the Gulf of California, after Stevenson (1971).

IV. ANALYSIS OF DATA

Geostrophic Calculations

The data collected in 1970 were used to obtain a general trend of the relative dynamic topography in the region between La Paz and Topolobampo. For this purpose the data of transects II and III were adequate; however, transect I was too far south of transect II (about 180 km) for surface contouring between them.

The 500 decibars surface was used as the reference level because most of the stations were sampled only to 500 meters. This reference level was also used by Roden and Groves (1959) and Griffiths (1968).

Assuming flow parallel to the dynamic contours, the relative dynamic topography of the sea surface shown in Figure 8a defines outflow from the Gulf of California over the eastern side of the entrance, off the coast of Sinaloa, and inflow over most of the western side. There is evidence of water flowing out on the western side, close to Baja California, indicated by a rise of the sea surface towards the west coast. Similar dynamic topography exists at 50 meters (Figure 8b) with weaker gradients. At 100 meters the features described above are still noticeable (Figure 8c).

The vertical distributions of geostrophic velocities across transects I, II and III, relative to 500 meters, were computed for

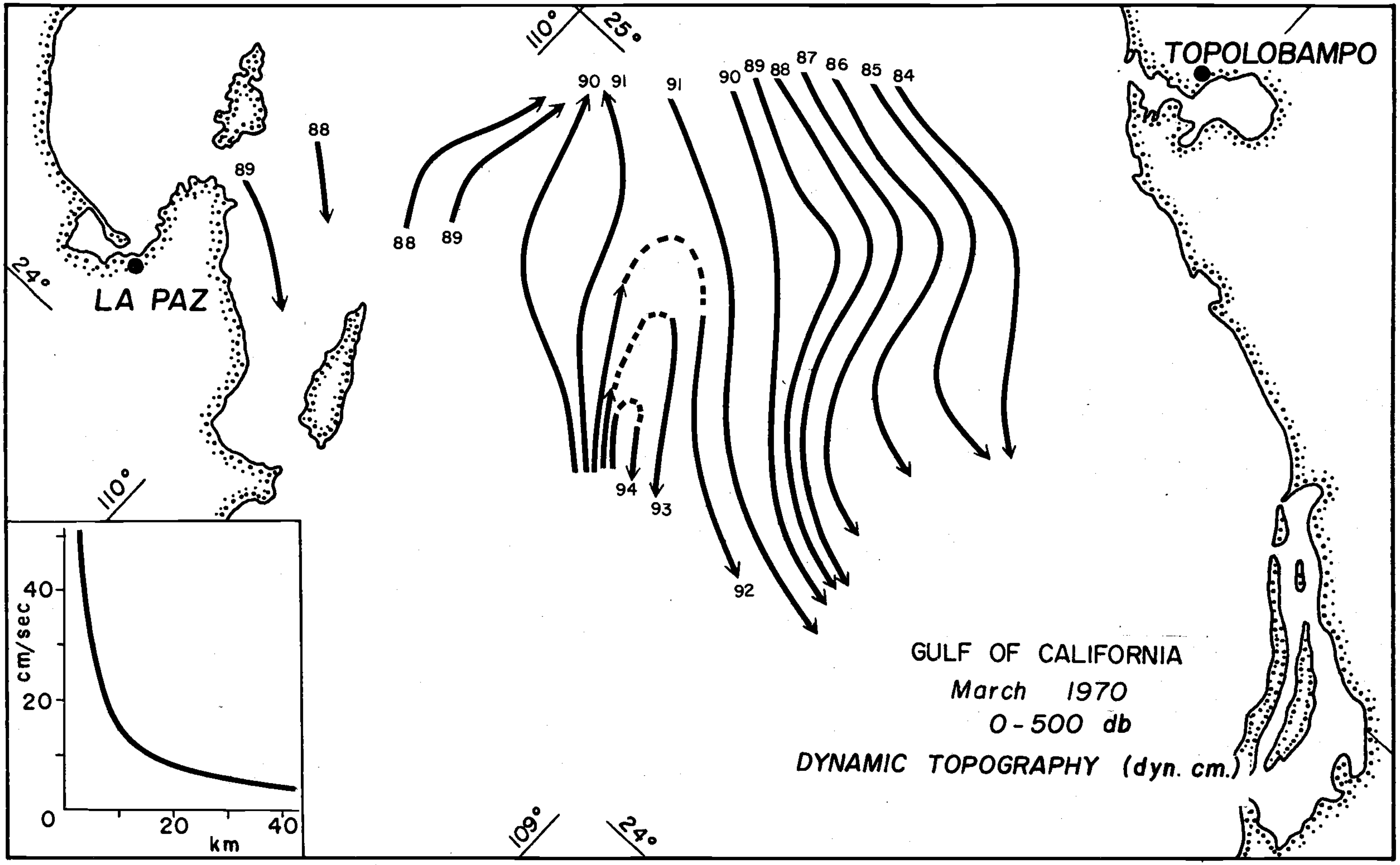


Figure 8a. Dynamic topography of the 0 over 500 decibars surface. The numbers indicate dynamic height (dyn. cm.) and the arrows indicate the direction of flow. The nomogram curve on the left gives geostrophic speed as function of separation between adjacent contour lines.

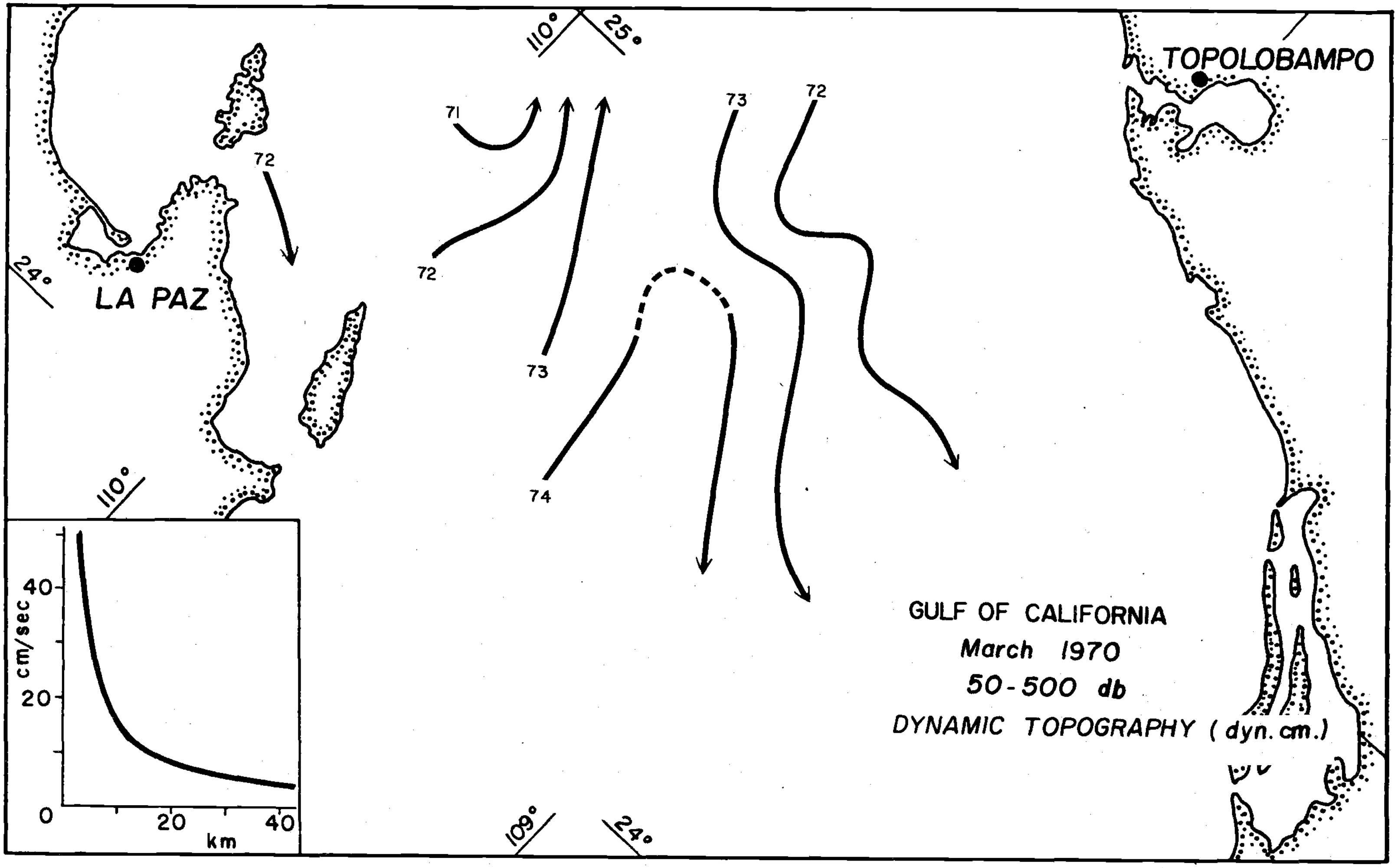


Figure 8b. Dynamic topography of the 50 over 500 decibars surface. The numbers indicate dynamic height (dyn. cm.) and the arrows indicate the direction of flow. The nomogram curve on the left gives geostrophic speed as function of separation between adjacent contour lines.

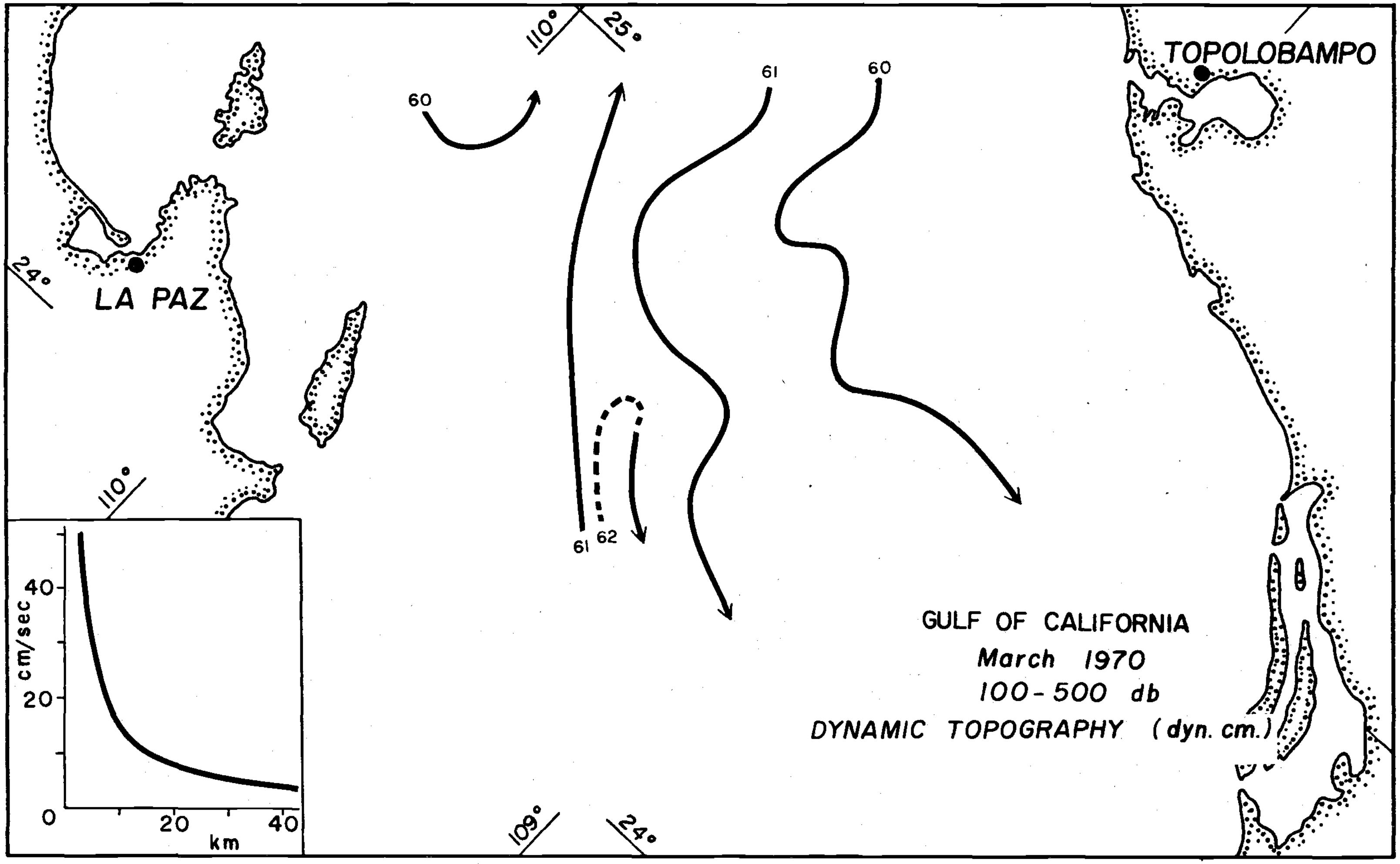


Figure 8c. Dynamic topography of the 100 over 500 decibars surface. The numbers indicate dynamic height (dyn. cm.) and the arrows indicate the direction of flow. The nomogram curve on the left gives geostrophic speed as function of separation between adjacent contour lines.

various depths (Figures 9a, b, c). There are well defined regions of inflow and outflow in the upper 300 meters. These may be the high speed cores detected by Roden (1972) when he sampled the region with more closely spaced stations.

Transect I, being closer to the open ocean shows alternate regions of inflow and outflow with a wide range in speeds (Figure 9a). Speeds associated with outflowing water reach 56 cm/sec at the surface between stations 129 and 130. This is the maximum value of the geostrophic speeds in the area under study. Other regions of outflow along transect I occur at both ends with speeds near 20 cm/sec on the eastern side and near 6 cm/sec on the western side. There are three regions of inflow in transect I with speeds up to 28 cm/sec near the surface. Some reversals of flow in the vertical are present above 100 meters but these involve very low speeds. In general, speeds decrease with depth and become negligible at 400 meters.

In transects II and III (Figures 9b and c) there are two regions of outflow at both ends of the transects, separated by a region of inflow near the middle and western part. Inflow speeds reach 40 cm/sec near the surface and are higher than those of outflow. There are no reversals of flow in the vertical in the upper 100 meters except for that in transect III, between stations 86 and 88. There are no abrupt changes in speed in the vertical but the layer

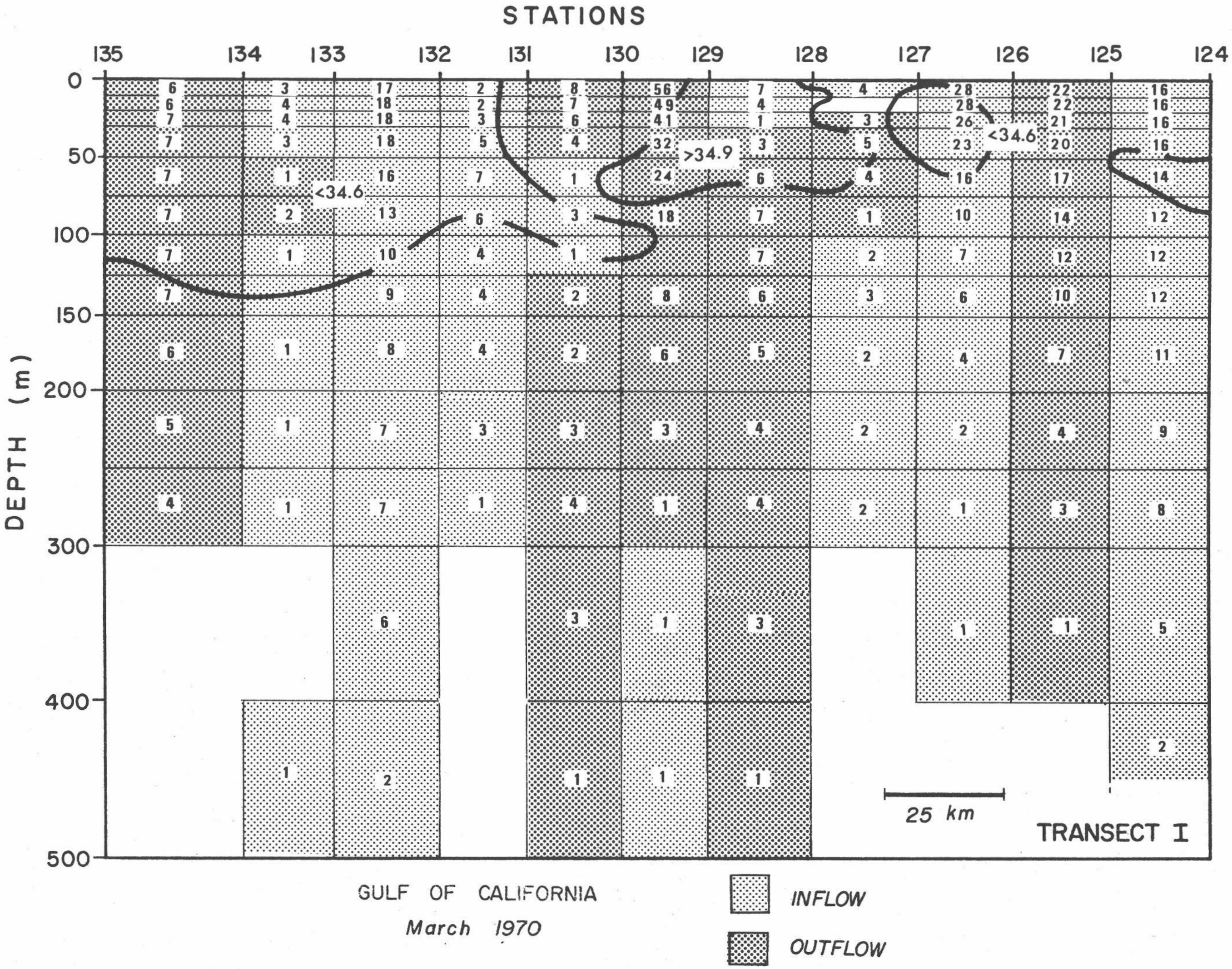


Figure 9a. Vertical distribution of geostrophic velocity (cm/sec) across transect I. The regions of low and high salinity are indicated.

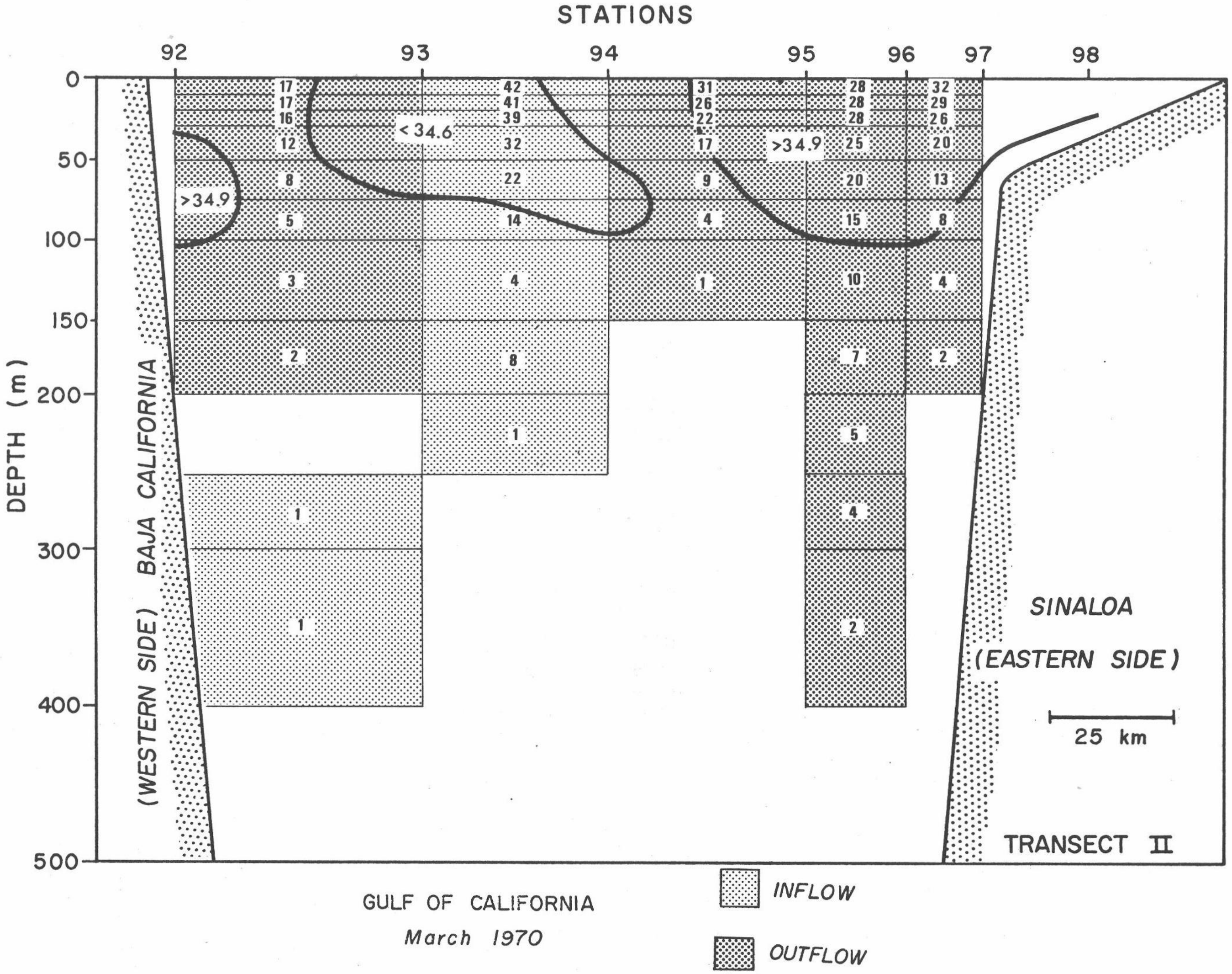


Figure 9b. Vertical distribution of geostrophic velocity (cm/sec) across Transect II. The regions of low and high salinity are indicated.

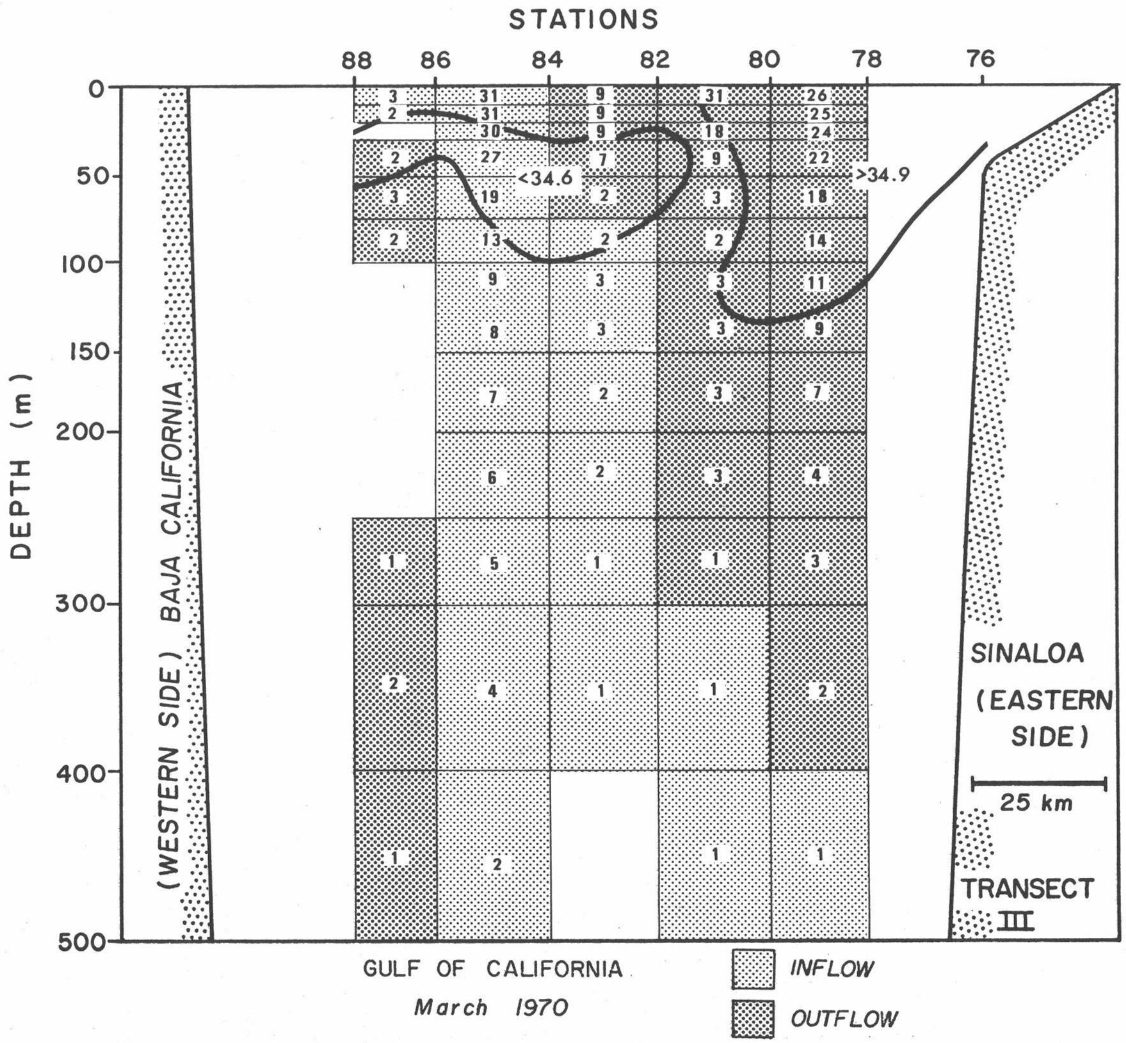


Figure 9c. Vertical distribution of geostrophic velocity (cm/sec) across transect III. The regions of low and high salinity are indicated.

of maximum shear is between 50 and 100 meters. At 250 meters speeds are below 5 cm/sec in transects II and III. Similar speeds occur down to 300 meters in transect I.

Geostrophic velocities across transect II were also computed assuming a variable reference level across the entrance to the Gulf. This reference level was proposed by Warsh and Warsh (1970) and varies from 200 meters in shallow water to 800 meters in deep water (Figure 10). The level proposed was obtained from data collected in February of 1957 about 100 km south of transect II. It was considered valid for the present data since there are no marked changes in the bottom topography or in the orientation of the coastline.

Transport by Geostrophic Currents

Transport by geostrophic currents across transect II was calculated for the upper 500 meters. The variable reference level yielded an inflow Q_i of 1.79 Sv and outflow Q_o of 1.84 Sv, indicating that there is nearly a balance in the water exchange across transect II in the upper 500 meters. The area above this depth is 35% of the total cross sectional area of the Gulf entrance at this location. The fixed reference level at 500 meters yielded Q_i = 1.25 Sv and Q_o = 2.40 Sv.

In Figures 9a, b, c the 34.6 $^o/oo$ and 34.9 $^o/oo$ isohalines that

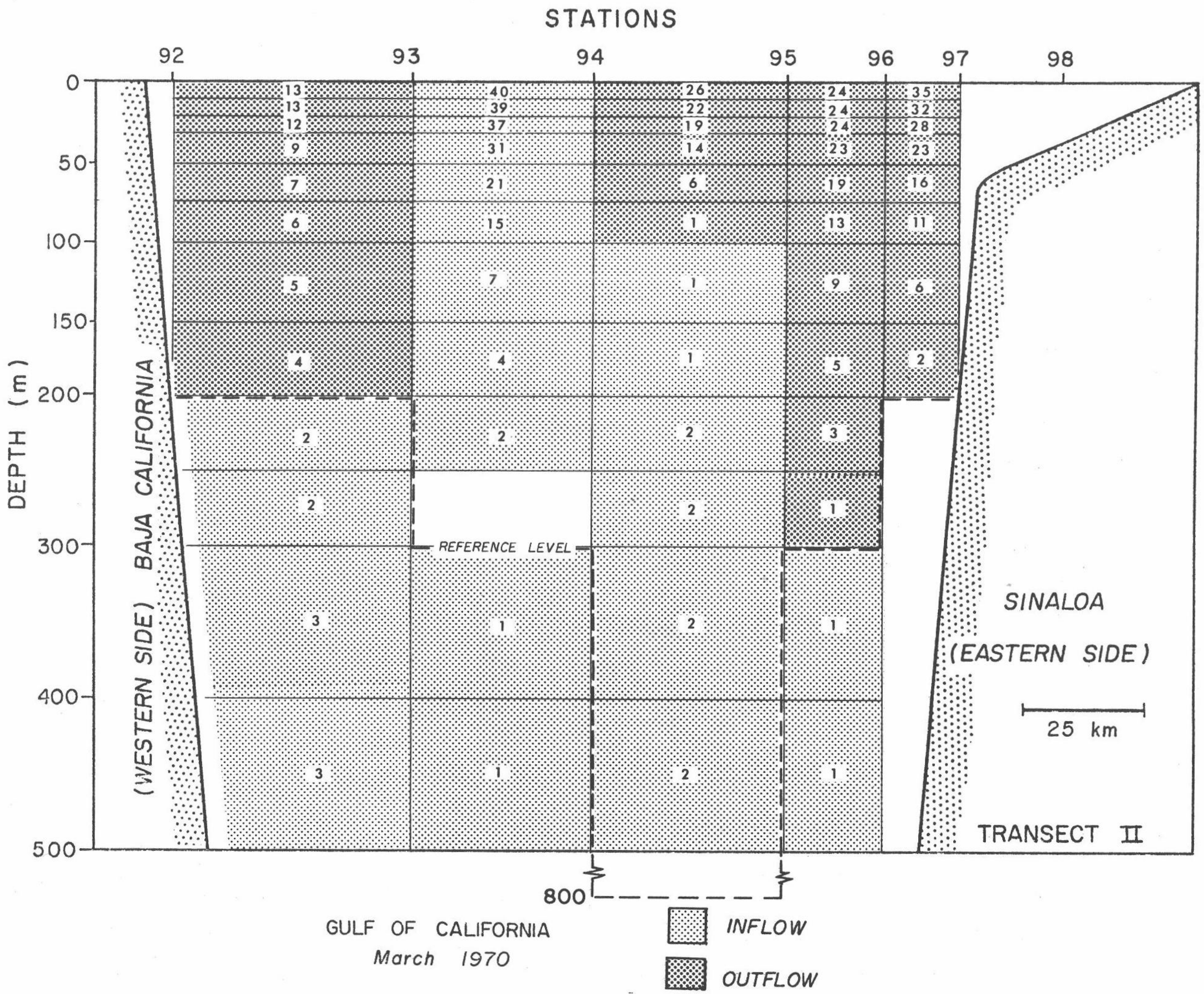


Figure 10. Vertical distribution of geostrophic velocity (cm/sec) across transect II, relative to a variable reference level.

define the cores of low and high salinity are superimposed on the vertical distribution of geostrophic velocity across the three transects. It is difficult to find a clear relationship between the salinity distribution and the direction of flow because in some cases the spacing between stations is similar to the horizontal extension of the cores. However, it can be observed that the high salinity water is flowing out in most of the cases and lower salinities are more associated with regions of inflow.

Drogue Measurements

A summary of the drogues observational program in the Gulf of California and the basic statistics of the drogues motion are given in Table 2. The results of the autocorrelation analysis are listed in Table 3. The drogue motion was also referred to the "along channel" and "across channel" axes shown in Figure 14. These were obtained by counterclockwise rotation of the cartesian coordinate system about 35 degrees so that the along channel axis coincides with the orientation of the coastline.

Unsmoothed drogue trajectories, as observed in the spring of 1970, are shown in Figures 11a, b, c. At drogue station 1, on the eastern side (Figure 1a), the current setting was to the southeast, almost parallel to the coastline. There is consistency in the direction of motion at the four depths (9, 50, 110 and 250 meters). The

Table 2. Drogue Statistics, Gulf of California, spring of 1970

Drogue station	Depth (m)	Duration (hrs.)	Mean speed (cm/sec) u:east	v:north	c	Direction Deg. true	Mean speed across channel	(cm/sec) along channel
1	9	26.5	17	-22	28	142°	1	-29
Mar 18	50	26.5	15	-16	22	137°	3	-22
	110	26.0	14	- 7	16	115°	3	-14
	250	26.0	8	- 8	11	133°	3	-11
2	7	18.0	-30	14	33	294°	-17	28
Mar 23	50	18.0	-10	4	11	291°	- 6	17
	110	18.0	- 7	4	8	298°	- 4	7
	250	16.0	0	0	0		0	0
3	7	25.5	42	1	42	89°	34	-23
Apr 3	50	25.0	27	1	27	88°	23	-15
	110	25.0	25	- 5	26	99°	18	-18
	250	24.0	22	0	22	91°	18	-13

Table 3. Results of autocorrelation and Fourier analysis of drogue observations in the Gulf of California, spring of 1970.

Drogue station	Depth (m)	Period (hrs.) T_x	T_y	Amplitude (km) A_x	A_y	ρ_x	ρ_y	N/2
1	9	17.5	11.3	0.7	0.2	1.38	1.27	51
Mar 18	50	4.3	13.5	0.1	0.4	1.59	2.13	51
	110	15.8	14.8	0.6	0.9	1.67	1.34	52
	250	26.8	12.0	0.5	0.6	1.77	1.30	54
2	7	12.0		0.6		1.22		38
Mar 23	50	14.0	14.0	1.1	1.5	1.17	1.05	38
	110	14.5	13.0	0.9	0.5	0.84	1.59	40
	250	10.5	10.0	0.7	0.3	1.12	2.09	31
3	7	10.8	22.0	0.4	0.9	1.27	1.43	47
Apr 3	50	25.0	14.0	1.2	0.8	1.11	1.36	43
	110	16.5	11.8	1.4	0.2	0.91	2.41	47
	250	11.8	13.5	1.0	0.5	1.72	0.87	43

drogue at 110 meters indicated onshore motion that also affected the drogue at 250 meters but to a small extent. This change in direction is not evident in the drogues trajectories at 9 and 50 meters. The trajectories at drogue station 2, on the western side (Figure 11b), indicate a resultant current to the northwest from the surface to 110 meters. The drogue at the surface moved faster and did not show the reversal in direction that affected the drogues at 50 and 110 meters. The displacement of the drogue at 250 meters was negligible and is not shown in the figure. At drogue station 3 (Figure 11c) the

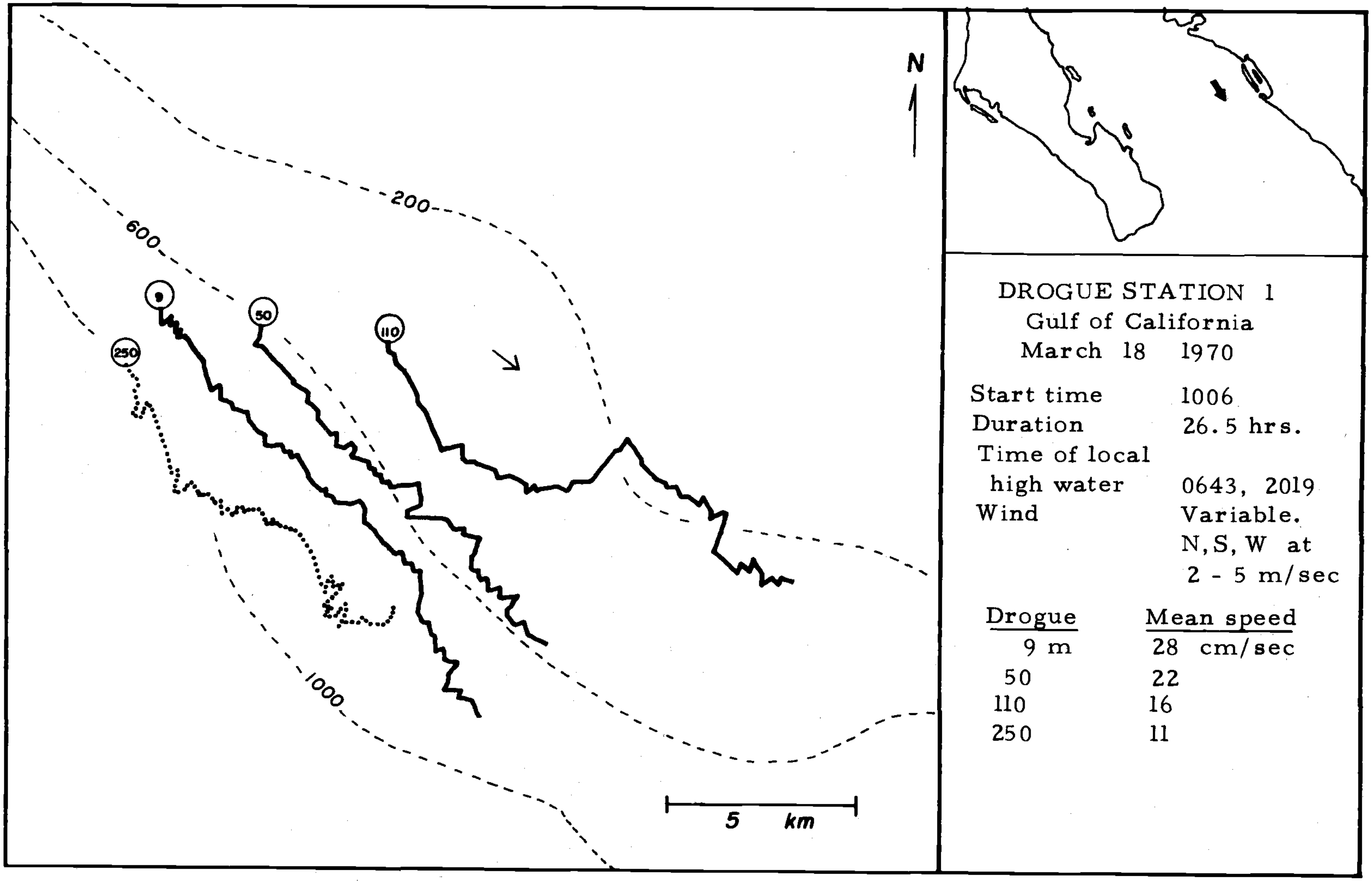


Figure 11a. Drogue trajectories at drogue station 1. The numbers in circles indicate the depth of measurement. Depth contours in meters.

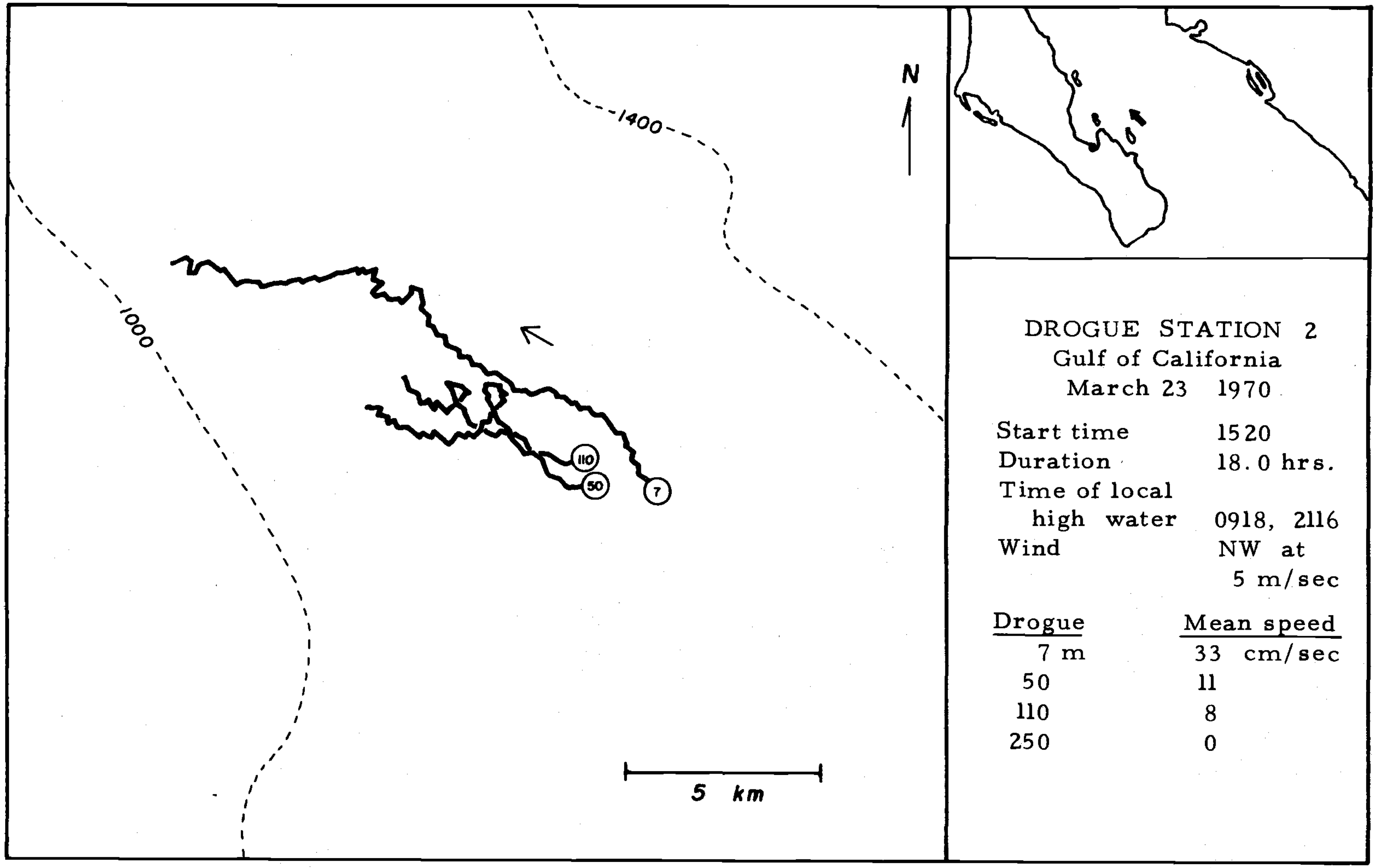
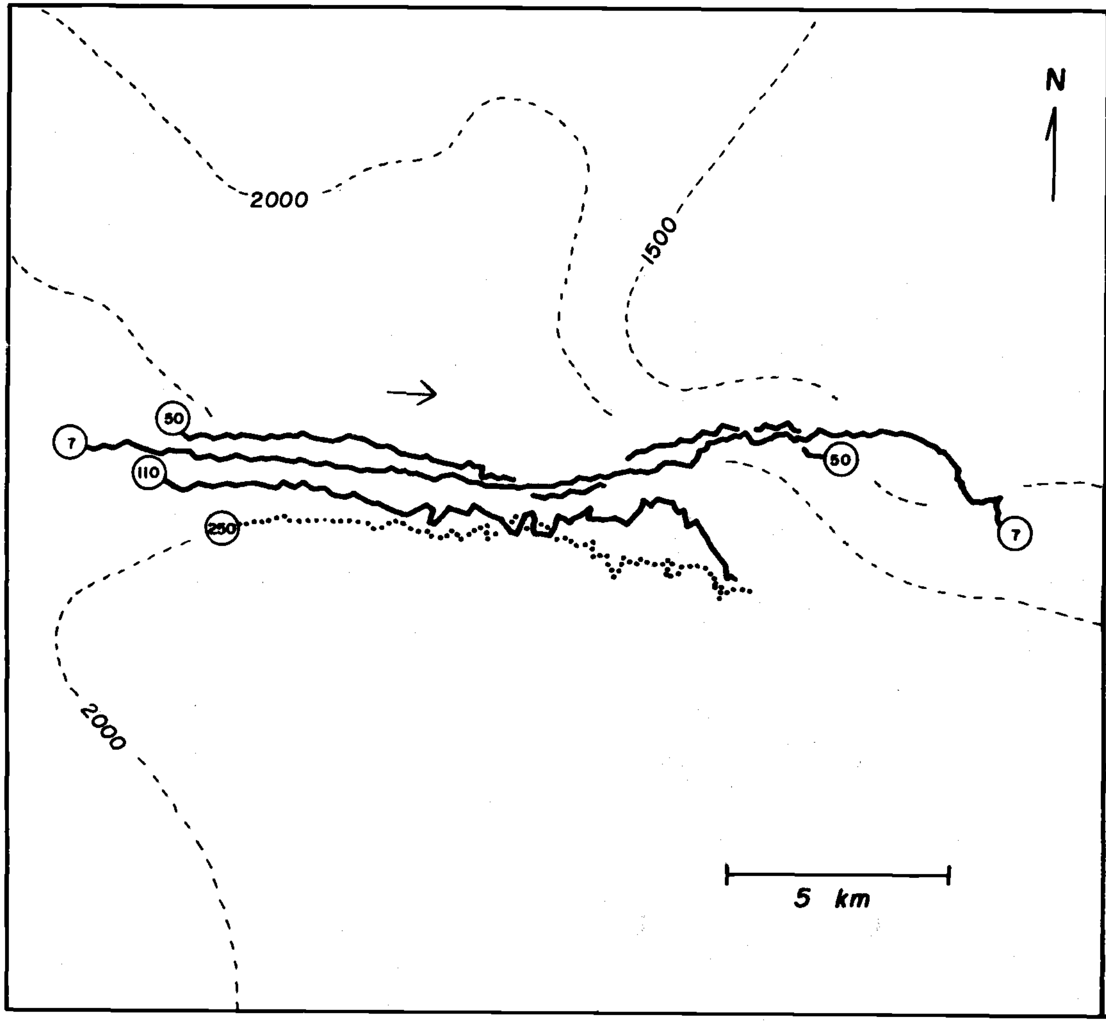
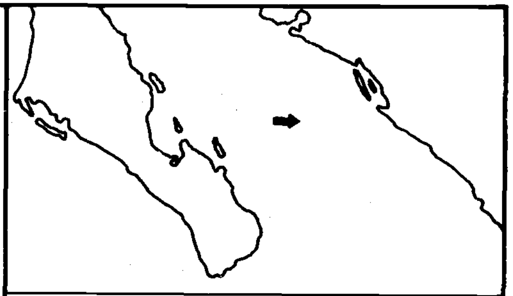


Figure 11b. Drogue trajectories at drogue station 2. The numbers in circles indicate the depth of measurement. Depth contours in meters.





DROGUE STATION 3
Gulf of California
April 3 1970

Start time	1311
Duration	25.0 hrs.
Time of local high water	0720, 2005
Wind	NW at 3 - 6 m/sec

Drogue	Mean speed
7 m	42 cm/sec
50	27
110	26
250	22

Figure 11c. Drogue trajectories at drogue station 3. The numbers in circles indicate the depth of measurement. Depth contours in meters.

drogues set in the middle part of the entrance moved in a constant eastward direction at the four depths.

As shown in Table 2, the mean speeds of drogue motion are relatively high, ranging from 28 cm/sec to 45 cm/sec near the surface (the upper 10 meters). The mean speeds decrease with depth in the three drogue stations but in station 2, on the western side of the Gulf, the speed decreases to near zero at 250 meters. At this depth, the speeds measured in drogue stations 1 and 3 are 11 cm/sec and 22 cm/sec, respectively.

The periods and amplitudes vary over a wide range as shown in Table 3. The dominant periods of the drogues motion along the y axis (T_y) are closer to the semidiurnal period of 12.5 hours than the periods of the motion along the x axis (T_x) which show more scattered values (Figure 15). From the 23 ρ values computed, 20 fall below 1.8 and from these, 12 are smaller than 1.3.

V. DISCUSSION

Water Masses

Sverdrup, et al. (1942) have stated that near 23° latitude north the cool subarctic waters that are transported south along the Pacific coast of North America by the California Current meet the warm equatorial waters. The region of the entrance to the Gulf of California lies on the eastern side of this extensive transitional area in which sharp boundaries between the water masses are absent (Kin'dyushev, 1970). This is one reason why various authors have given different classifications of the kinds of waters in this region.

There is agreement regarding the waters found roughly between 150 and 400 meters at the mouth of the Gulf. This water was formed near the equatorial region of the southern hemisphere and spread northward. It can be identified as a subsurface salinity maximum near 34.8 ‰ (Roden and Groves, 1959; Wyrtki, 1967; Kin'dyushev, 1970; Warsh, et al., 1973). This is the Subtropical Subsurface water defined by Wyrtki (1967) and can be easily identified at the mouth (transect I) between 125 and 200 meters but in transects II and III the maximum is obscured by the cores of high salinity water. It is present, however, below the low salinity water (Figures 3b, and c).

The origin and boundaries of the water above 150 meters are more difficult to establish. The Gulf of California is the only important source of high salinity surface water (greater than 34.9 $^o/oo$) in the eastern north Pacific Ocean. This water is formed inside the Gulf by modification of equatorial water. It was classified by Wyrtki (1967) as Subtropical Surface water. Warsh, et al. (1973) considered that this name is misleading since it may imply that the high salinity water has its origin in the South Pacific where Wyrtki described the Subtropical water. They stated that the name Gulf Water is more adequate, following the nomenclature used by Roden and Groves (1959), Griffiths (1968), Kin'dyushev (1970) and Stevenson (1970). Most of this high salinity water can be seen as a core on the eastern side of transects II and III. There is also evidence of high salinities on the western end of transect II and in the middle part of transect I.

Water with temperature above 15 ^oC and intermediate salinity (34.6 $^o/oo$ to 34.9 $^o/oo$) is Subtropical Surface water according to Wyrtki (1967). It is derived from modification of water carried south by the California Current when it reaches lower latitudes and mixes with Tropical Surface water near 20^o north latitude.

The origin of water with relatively low salinity (below 34.6 $^o/oo$) is more controversial. There are two main sources of low salinity water that may affect the region of the entrance to the Gulf. One is the California Current water from the north and the other is the Tropical Surface water from the south, as defined by Wyrtki (1967).

Previous research identified this water as California Current water. Warsh, et al. (1973) pointed out that the water with salinities lower than 34.6 $^{o}/oo$ in the region of the entrance to the Gulf in the summer of 1967 was a mixture of California Current surface water and Tropical Surface water. They called this mixture Transition Water A.

The following facts are important in relating to the low salinities found in the Gulf of California during the present study (early spring):

(1) The Tropical Surface water is a thin layer of low salinity (less than 34.0 $^{o}/oo$) in the upper 20 or 50 meters in the eastern tropical Pacific Ocean (Eastropac Atlas, 1971, 1972; Wyrtki, 1967; Tsuchiya, 1968).

(2) The surface circulation of the open ocean in the vicinity of the mouth of the Gulf is to the south and southeast during winter and spring and in the opposite direction (to the northwest) during the summer and fall in response to the change in direction of the trade winds (Wyrtki, 1965) (Figure 16).

(3) California Current water has been detected throughout the year near Cabo San Lucas from the surface to 150 meters or even 200 meters (Stevenson, 1970).

These three conditions suggest that at the time of the observations for this study, Tropical Surface water did not reach the region of the entrance to the Gulf of California and the low salinity water is assumed to have origin in the California Current.

Summarizing, the water masses observed in the spring of 1970 in the region of the entrance to the Gulf of California are:

Water Masses	Salinity $^{o}/oo$	Depth m
California Current water	< 34.6	0 - 150
Subtropical Surface water	34.6 - 34.9	0 - 150
Gulf water	> 34.9	0 - 100
Subtropical Subsurface water	34.55 - 34.80	200 - 500

These kinds of water are in agreement with previous studies when considered in terms of their thermohaline properties. However, the available literature indicates that the spatial distribution of these waters in the region of the entrance to the Gulf has marked changes with time. Gulf water may spread across the mouth as a thin surface layer in the upper 30 meters or occur as subsurface cores in the upper 100 meters. The same distribution applies to California Current water. The distribution of these two waters, in terms of their salinity, were inspected by the author in all the transects available for the region of the entrance to the Gulf from 1939 to 1969, in order to see if the distribution observed in the spring of 1970 corresponds to a seasonal form of occurrence. No seasonal pattern of distribution was found probably as a result of the complex circulation in this area.

A limited amount of Gulf water is supplied to the Pacific Ocean as inferred from the decrease in size of the high salinity cores towards the south. An intermittent outflow of this water was suggested by Stevenson (1970) who detected it flowing out of the Gulf not further south than Cabo Corrientes. To maintain a salt balance, an outflow of high salinity water is necessary in order to compensate for the high evaporation that takes place inside the Gulf and avoid the salt accumulation. This explains why the high salinity Gulf water is almost always found in the regions of outflow.

California Current water has been observed during the year near Cabo San Lucas and sometimes turning around the tip of Baja California into the Gulf. Stevenson (1970) reported maximum penetration of California Current water into the Gulf during April. A similar condition was found during the present study in late March of 1970. The low salinity water was detected inside the Gulf of California 180 kilometers north of the mouth, in transect III. There are no previous reports of this water flowing into the Gulf as far as 25° latitude north. This fact may be the influence of changes in the circulation of the California Current. The southernmost extension of this current takes place in spring and coincides with the maximum penetration of low salinities into the Gulf reported by Stevenson (1970) and the results of this study.

Geostrophic Circulation

Mixing of the water masses previously described produces a complicated baroclinic structure and circulation associated with this condition in the region of the entrance to the Gulf. The currents computed by the geostrophic method are induced by the horizontal pressure gradients that result from the mass distribution. The observations discussed in this study indicate that two processes are the main causes of these pressure gradients:

(1) The density field from the presence of different kinds of water, and (2) the wind stress at the sea surface that produces a sloping sea surface. These two processes are difficult to evaluate separately. Fomin (1964) stated that the currents resulting from the pressure gradients produced by wind can be calculated by the geostrophic method, together with those arising from the density field, but the velocity of the steady wind driven current at the surface can not be obtained by this method.

The sloping isopycnals on the eastern margin of the Gulf in transects II and III can be explained by the divergent flow that is produced by the northwesterly winds that prevailed at the time of sampling. The wind blowing parallel to the east coast of the Gulf tends to move the surface water away from the east coast and to pile it against the coast of Baja California. More dense water from lower layers replaces less dense surface water on the eastern side of the transects and produces the upward displacement of isopycnals. This density distribution is characteristic of the upwelling regions. When the density field tends to reach a stable position, the current that results, assuming geostrophic equilibrium is towards the south, with more dense water on the left side and less dense water on the right side, looking downstream. The geostrophic computations in this study indicate the presence of this strong current to the south on the eastern side of the Gulf (Figures 8a, 9b and c).

The flow pattern is more irregular on the western side of the Gulf. The presence of the low salinity water from the California Current can not be explained by the wind induced density distribution inside the Gulf but it is probably the result of the open ocean circulation outside the Gulf.

The presence of eddies at the mouth of the Gulf can be inferred from the surface dynamic topography and from the reversals of flow along the transects. Griffiths (1968) has shown the surface dynamic topography in this region for the spring of 1960 and the pattern of the dynamic contours supports the possibility of eddies. These gyres may be compared to those that develop in the nearshore region of the California Current south of Point Conception, California, and south of Punta Eugenia, Baja California, shown by Schwartzlose and Reid (1972).

The distribution of the regions of inflow and outflow across the entrance does not fully agree with what other authors have described, but some common features were found in spite of the marked variability of the currents. From the available information on geostrophic currents in the region of the entrance, it seems that most of the outflow above roughly 200 meters takes place on the western side of the Gulf during June, July, August and December (Stevenson, 1970; Warsh and Warsh, 1971; Roden, 1972; Warsh, _et al._, 1973). During this study it was found that during March of 1970 outflow prevailed on the eastern side of the Gulf with minor evidence of outflow on the west, close to Baja California. This observation agrees with the results of Griffiths (1968) in the spring of 1960 and Stevenson (1970) in January, February and April of 1967.

Based on past evidence and the results of this study it is proposed that the change in the open ocean circulation from a southeast direction in winter and spring to a northwest direction in summer and fall forces an eddy that in winter and spring induced inflow on the western side of the Gulf, near Baja California, and outflow on the eastern side, near Sinaloa. This outflow becomes intensified by the circulation in the upwelling region. During summer and fall inflow takes place on the eastern side and outflow occurs on the western wide. This proposed circulation for March and September is illustrated in Figure 16 where the surface circulation based on ship drift records, after Wyrtki (1965), is also shown. There are only a few ship drift records at the entrance to the Gulf in March and these do not show inflowing water probably because of the large scale of sampling.

Transport by Geostrophic Currents

The fixed reference level at 500 meters yielded transports across transect II similar to previous results by Roden and Groves (1959) as shown in Figure 12. The transports computed using the variable reference level proposed by Warsh and Warsh (1971) are $Q_i = 1.79$ Sv and $Q_o = 1.84$ Sv. The reference level at 500 meters gave $Q_i = 1.25$ and $Q_o = 2.40$ Sv. Two factors can account for this discrepancy. One is the choice of reference level and another is the lack of data close to the margins of the Gulf.

The relatively high speeds (greater than 10 cm/sec) are restricted to the upper 100 meters and these differ by no more than 15% in both methods. Speeds as low as 2 cm/sec in the lower 300 meters of the section produce a significant portion of the total transport across the section. This transport can appear as an inflow or outflow depending on the reference level being used. This fact explains most of the differences in the transports relative to both reference levels.

Circulation from Drogue Analysis

The mean velocities of the drogues are the average over one day. The circulation inferred from the drogue trajectories observed

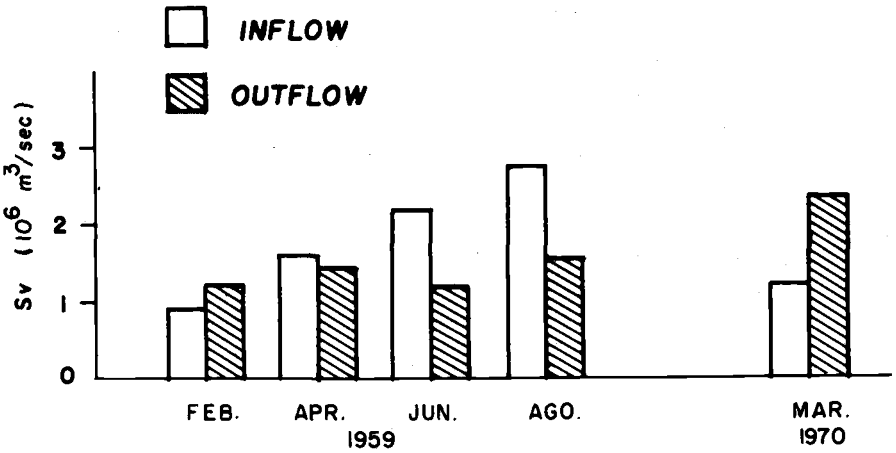


Figure 12. Transport by geostrophic currents in the upper 500 meters across the entrance to the Gulf of California after Roden (1959) and in March of 1970.

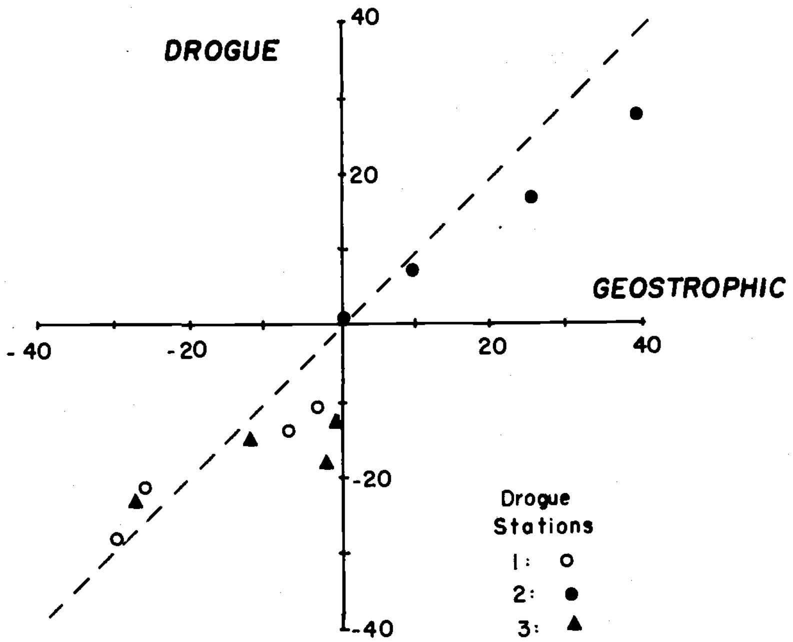


Figure 13. Drogue versus geostrophic velocities in the along channel direction; (+) inflow, (–) outflow. The dashed line is at 45° for reference.

in this study agrees in general with the geostrophic circulation that represents the conditions averaged over about one week. The speeds computed by both methods show an acceptable agreement. The speeds at 10 and 50 meters calculated by both methods have better agreement than those at 100 and 250 meters. The drogues speed in the along channel direction are compared with the geostrophic speeds in the same direction in Figure 13.

The regions of inflow and outflow inferred from the dynamic topography are also shown by the drogues motion except for the drogue station 3, in the middle of transect II. At this place there is a strong eastward velocity from the surface to 250 meters, at an oblique angle with respect to the geostrophic flow lines near station 3 (Figure 14). This can be the effect of the time difference in measurement since drogue station 3 was made 10 to 15 days after the first two drogue stations. Another explanation that seems more reasonable is the presence of a gyre as discussed previously in relation to the dynamic topography. This gyre produces inflow close to Baja California, then the current turns east and the water flows out on the eastern side with across channel circulation in the middle.

It has been found that the trajectories of water particles are parallel to the dynamic contours only in exceptional circumstances. Discrepancies are more likely to occur especially in regions of convergence and divergence where vertical motion is not negligible

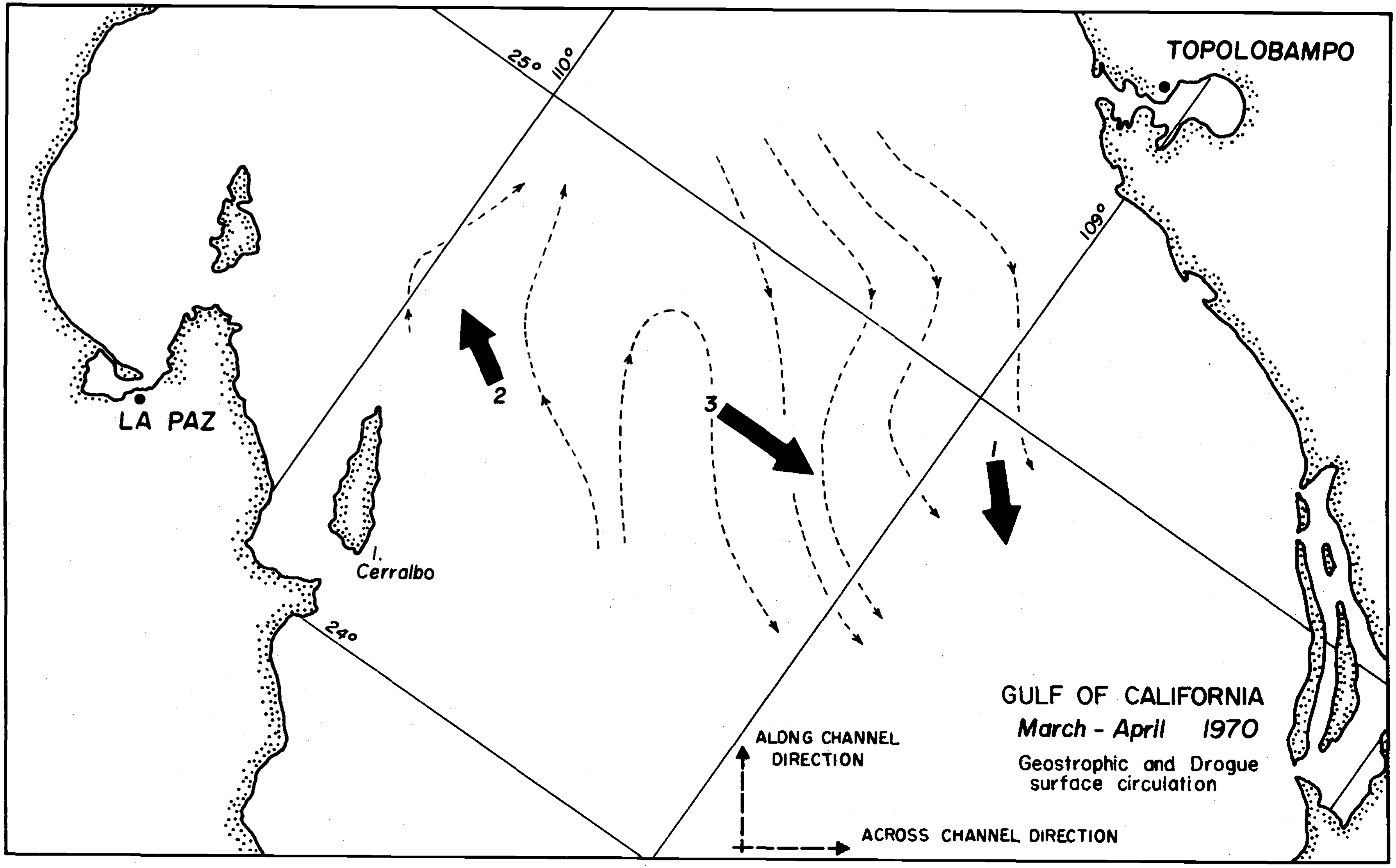


Figure 14. Surface geostrophic flow (-----) and drogue displacements (arrows) at drogue stations 1, 2 and 3.

(Parr, 1938). Taking into account the time difference in observations, the limitations of the geostrophic method and the complex thermohaline structure of the region under study, it can be stated that the direct and indirect methods used to study the currents have fair agreement in the upper 100 meters.

The use of the geostrophic method in the Gulf of California is questionable because of its small extension. Reid (1959) has found that an error of 20% is introduced in the calculations of geostrophic currents by errors in the determination of temperature, salinity, pressure and position of the ship when spacing between stations is 80 kilometers. The error increases with smaller spacing. In this study, the spacing between stations is less than 80 kilometers.

The drogue measurements can be used to estimate the reliability of the geostrophic currents, keeping in mind that current measurements and hydrographic stations were not simultaneous and that these methods did not give averages of the currents over the same period of time. Since the drogues motion is relative to a point fixed to the sea bottom, the observed circulation gives the total current in the water column. The duration of the measurements is from one to two semidiurnal periods so the tidal effects are assumed to cancel. The baroclinic part of the circulation is estimated by the geostrophic method but not the barotropic part. Comparing the results of the two methods (Figure 13) it seems that the circulation in the upper layers (above 100 meters) is mainly baroclinic since at 10 and 50 meters the geostrophic and drogue measured currents have agreement better than 70% at drogue station 2 and better than 85% at drogue stations 1 and 3.

For this particular study, the geostrophic method gave an acceptable description of the general circulation in the region of the entrance to the Gulf of California in the upper 100 meters where the currents were stronger.

The drogue series were affected by short time variations in velocity but the time interval of observation was not sufficient to make a general statement regarding the periodic variations. Since the length of measurement is contained within the inertial period at 25^{o} latitude north (28 hours) only the period of the semidiurnal tide (12.5 hours) may be present in the drogue motion. As can be seen in Table 3, the dominant periods found by autocorrelation vary widely. Only the periods of oscillation along the y axis are close to the 12.5 hours period. Grijalva (1972) has computed tidal amplitudes and currents for the Gulf of California using numerical techniques to solve the hydrodynamic equations. The theoretical computations of the M_2 tide and associated currents in the region of the entrance to the Gulf indicate that these currents will produce an oscillatory motion predominantly in the north-south direction (along the y axis) with maximum speeds near 10 cm/sec. If this is the case, the greatest amplitudes in the drogue trajectories should have occurred in the y axis and the dominant period of this oscillation, T_y, would be close to the semidiurnal period of 12.5 hours. This seems to be the only reasonable explanation for the distribution of the dominant periods listed in Table 3 and illustrated in Figure 15. It can be seen that the periods T_y are closer to 12.5 hours than the periods T_x.

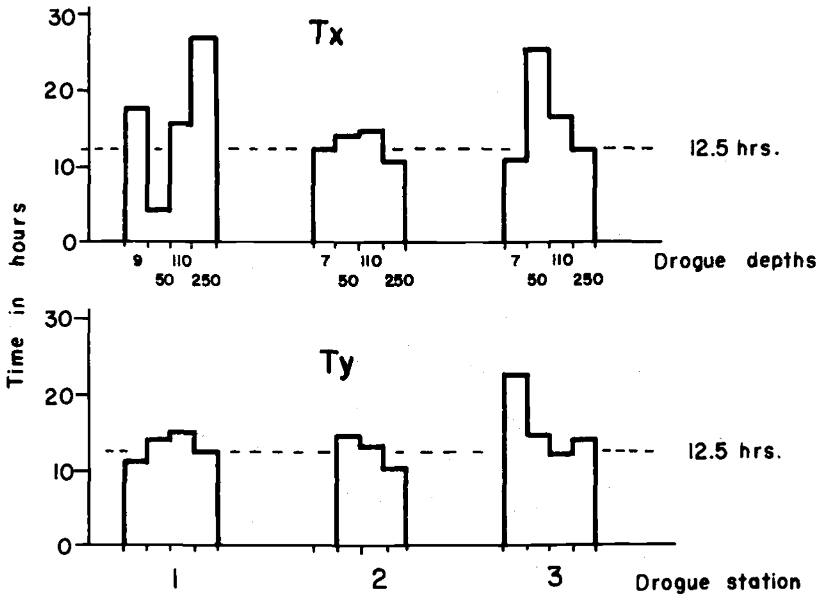


Figure 15. Dominant periods of the x and y components of the drogue motion at four depths.

VI. SUMMARY AND CONCLUSIONS

The water masses above 500 meters in the region of the entrance to the Gulf of California in March of 1970 were studied in terms of their thermohaline properties. The influence of the circulation outside the Gulf was also taken into account to explain the presence of low and high salinity water.

The water masses observed in this study above 150 meters are:

--California Current water, on the western side of the Gulf.

--Subtropical Surface water, between and under the cores of low and high salinity water.

--Gulf water, on the eastern side of the Gulf.

From 150 to 500 meters the water has the characteristics of Subtropical Subsurface water.

The geostrophic circulation relative to 500 meters defined regions of inflow and outflow to and from the Gulf. These regions were probably associated with a gyre in the region of the entrance. The calculated geostrophic speeds were variable but commonly in excess of 20 cm/sec near the surface and less than 3 cm/sec below 300 meters.

The circulation inferred from the drogue observations supported the possibility of meandering currents. Comparing the geostrophic currents with those measured with drogues it can be seen that the circulation above 100 meters was mainly baroclinic. The geostrophic method gave an acceptable description of the circulation in the upper 100 meters probably because of the marked differences in dynamic height over distances of about 20 kilometers. However, difficulties were found near the coast where the reference level could not be extended. Discrepancies between geostrophic and drogue measured speeds existed between 100 to 250 meters, probably related to short time variations in the currents.

The water mass distribution and the geostrophic and drogue analysis support the presence of a gyre in the region of the entrance to the Gulf of California, with clockwise motion in winter and spring and counterclockwise motion in summer and fall (Figure 16).

From the periods computed by autocorrelation analysis of the drogue series, 70% were between 10 and 15 hours suggesting the influence of the semidiurnal tide.

The drogue measurements proved to be useful in describing the variable currents in this area. More extensive drogue series will yield a better estimate of the influence of the tides and also will help to verify the theoretical model for the tides and tidal currents in the Gulf of California.

Once more, the oceanographic conditions in the region of the entrance to the Gulf of California were found to be complex and

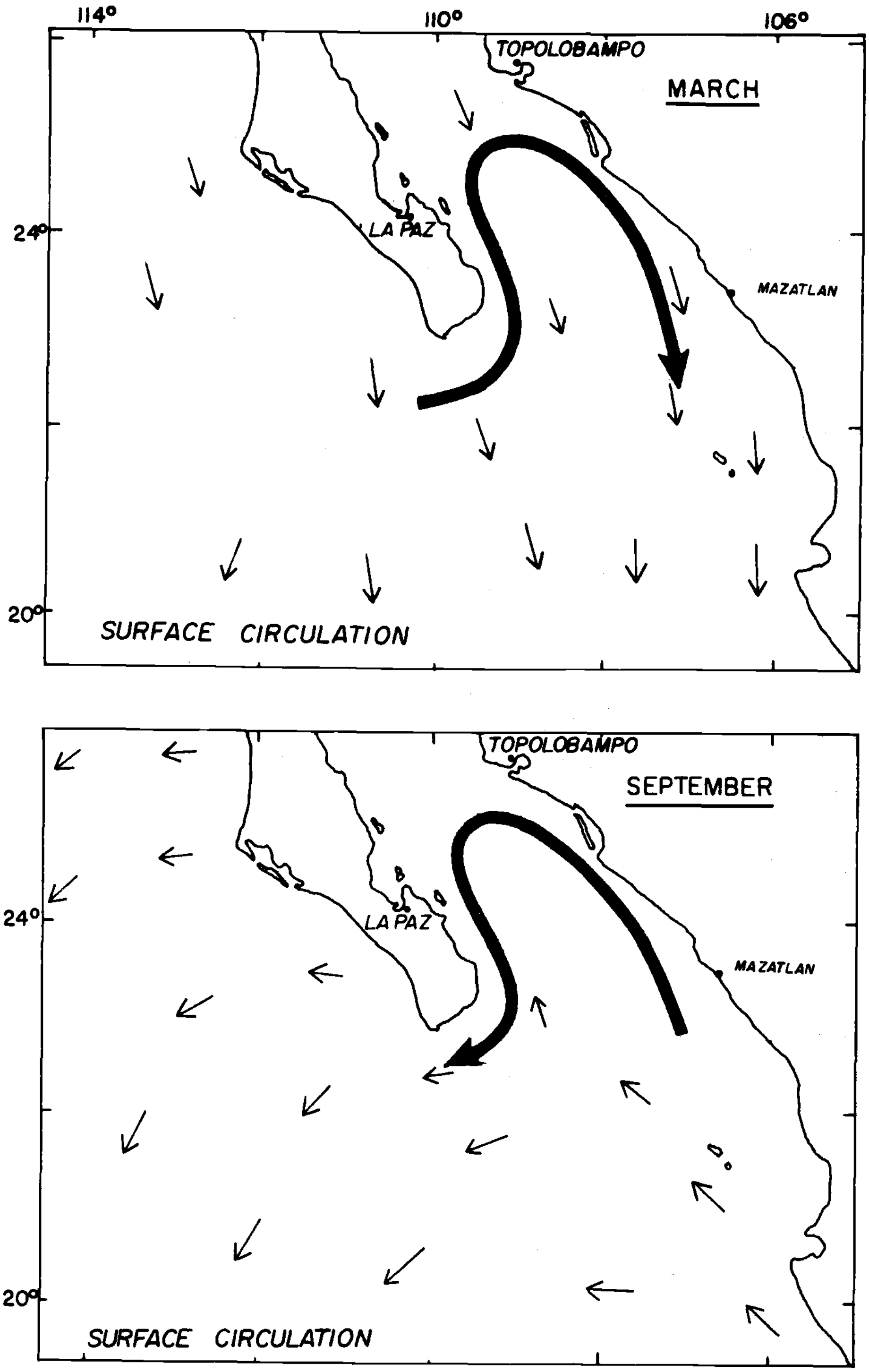


Figure 16. Surface circulation from ship drift records (after Wyrtki, 1965) and the proposed location of the gyre (heavy line).

with short time variations. It seems reasonable to think that future efforts to understand the physical conditions of the Gulf should be oriented first to regions that might be less complicated. However, the suggested possibility of a gyre at the entrance to the Gulf could be studied by means of long term ship drift records obtained by the ferries that go across the Gulf's entrance from La Paz to Mazatlan and from Cabo San Lucas to Cabo Corrientes. These ships could also be used to measure temperature and salinity continuously to study the time variation of the surface water masses.

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