SEASONAL VARIATION OF TEMPERATURE AND SALINITY AT 10 METERS IN THE CALIFORNIA CURRENT

RONALD J. LYNN, *Oceanographer*
Bureau of Commercial Fisheries Tuna Resources Laboratory
La Jolla, California

INTRODUCTION

The seasonal variation of temperature and salinity at 10 meters in the California Current is examined from the CalCOFI[1] data record, 1950–62. The CalCOFI station pattern off California-Baja California (Figure 1) has been occupied repeatedly since 1950. Surveys have been conducted on almost a monthly schedule although only a portion of the station pattern was covered each time. Only four surveys were conducted in 1961 and 1962. The sampling frequency of salinity for 1950–62 is shown in Figure 2. At some of the stations temperature was measured a few more times than salinity. Harmonic curves, comprised of the annual and semiannual components, were fitted to each station record by regression analysis using the method of least squares. The harmonic curves provide the description of seasonal variation. Along with the regression analysis are descriptive statistics.

The California Current System

The California Current is the eastern limb of the anticyclonic gyre that dominates the North Pacific Ocean. It is a broad sluggish current characterized by cool, low-salinity water. Warm high-salinity water is found to the west (central North Pacific) and south (vicinity of the Gulf of California). Upwelling along the coastal boundary of the current introduces cool, usually high-salinity water to the surface layer. Upwelling is the process whereby the wind component paralleling the coast (northwesterly) drives the surface water offshore; these waters are replaced by deeper waters.

The North Pacific gyre is largely wind-driven. Seasonal variation of the winds is indicated by seasonal variation of the strength and location of atmospheric pressure cells. The currents respond to variations in wind. This system was qualitatively described for the California Current region by Reid, Roden, and Wyllie (1958). A strong northerly wind component in spring through fall strengthens the Current. In winter the northerly component weakens or reverses and a countercurrent develops along portions of the coast. The seasonal variation of the winds has a most noticeable effect on coastal upwelling. Upwelling is strongest when the north and northwest winds are strongest. This situation occurs off Baja California in April and May, off southern and central California in May and June, off northern California in June and July, and off Oregon in August (Reid, Roden, and Wyllie, 1958).

The largest and most complex changes in circulation occur in the coastal region. A countercurrent is present in late fall, winter, and early spring from central California to British Columbia (cf. Sverdrup, Johnson, and Fleming, 1942; Schwartzlose, 1963). A nearly permanent eddy is found among the Channel Islands off southern California. The eddy is weak or nil in March, April, and May (Schwartzlose, 1963; Reid, 1965). The countercurrent is usually continuous around Point Conception in November, December, and January. There is no countercurrent along northern Baja California, but major eddies do occur off southern Baja California.

An atlas of sea surface dynamic topography (referenced to 500 decibars) of the CalCOFI data is under preparation at the Scripps Institution of Oceanography (SIO). The contours and gradients define the direction and speed of the geostrophic currents.

The variations of circulation and upwelling have a pronounced effect on the seasonal variation of temperature and salinity. The seasonal variation of these characteristics was discussed at length by Reid, Roden, and Wyllie (1958). They gave representative curves of the variations for diverse areas constructed from monthly means of CalCOFI data, 1949–55, and other sources.

The following paragraphs are quoted from a review of the earlier work by Reid (1960, p. 81). In place of seasonal variation curves to which his paragraphs refer, the reader may examine similar figures of this paper (Figures 8, 10, 13 and 14).

". . . Far offshore the variation, which is principally the result of variation in radiation and exchange with the atmosphere, has a simple pattern with the greatest range in the highest latitude. Near the coast in the region of strong upwelling north of 34°N. the seasonal range is reduced and the cool period lengthened by upwelling. Between 28°N. and 34°N. the upwelling occurs earlier in the year, more nearly at the period of the offshore seasonal minimum, and increases the seasonal range. South of 28° N. it is the fall and winter countercurrent which accounts for the high range and delays the low until late spring.

"The seasonal variation in surface salinity . . . indicates that the direct effect of evaporation and precipitation is small, and, indeed, there is little coherence in the variation of the northern offshore stations. Inshore it is again the processes of upwelling in the north and the countercurrent in the south which dominate the seasonal variation. The effect of the spring and summer upwelling of deeper water to the surface in the north causes a wide range with the maximum value of salinity in summer. In the south the winter countercurrent brings highly saline water northward along the coast giving a maximum in winter. The two effects tend to cancel each other in the middle region between 28°N. and 34°N. latitude."

Recently, the seasonal variation of temperature and salinity at diverse levels in the Point Conception (Point Arguello) region has been examined in detail (Reid, 1965).

[1] California Cooperative Oceanic Fisheries Investigations.

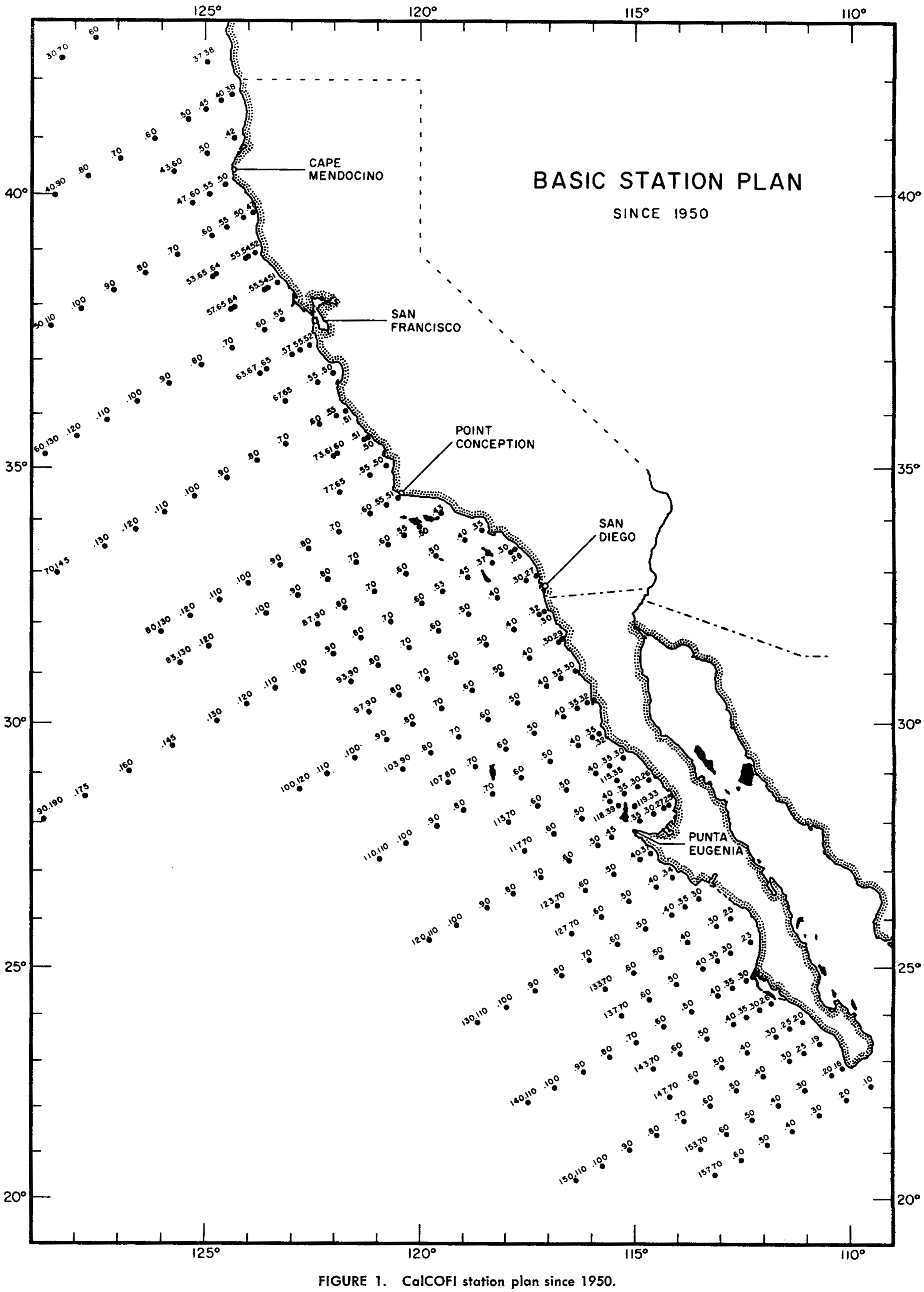

FIGURE 1. CalCOFI station plan since 1950.

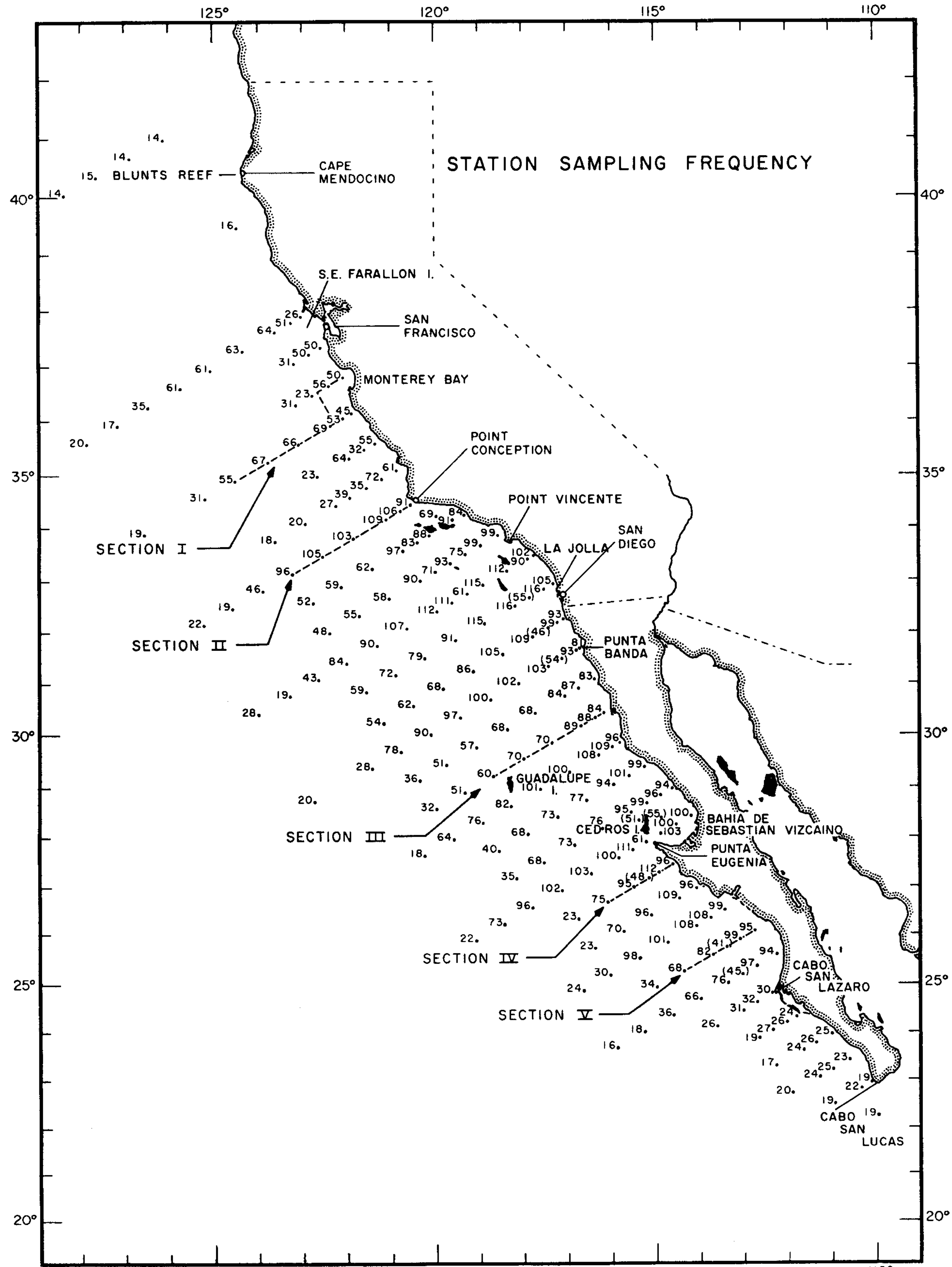

FIGURE 2. Station positions of data records used in the regression analysis and their sampling frequency, 1950—62. Sections refer to Figure 14.

The papers cited have described the major features of the variations in temperature and salinity in the California Current region. The present study employs a totally different method of analysis which substantiates the previous findings. Detail is provided in some areas and for some months that has not previously been available. Almost all of the statistical treatment is new.

California Cooperative Oceanic Fisheries Investigations Atlas No. 1 (1963) contains distributions charts of 10-meter temperature and salinity for each CalCOFI cruise, 1949–59. The atlas also presents charts drawn from 10-year monthly means of temperature and salinity. Near the end of this paper a brief comparison is made between the mean distribution charts of the atlas and those derived from the present analysis.

THE DATA

The CalCOFI data through 1959 are published in the series, Oceanic Observations of the Pacific. Data for more recent cruises are available in the data report series (unpublished) of the University of California Scripps Institution of Oceanography.

Records for 222 stations were selected for analysis from the CalCOFI 10-meter data for 1950–62 according to criteria of occupancy and location (Figure 2). Thirty percent of the stations were occupied 14 to 50 times, and the remainder 51 to 119 times. The stations with the lesser frequency of sampling are found at the seaward extreme of the station pattern, off Cabo San Lazaro and south, and scattered among the stations north of Point Conception. These station records were used to extrapolate charting of the distributions beyond the better sampled areas. The observations are not evenly distributed throughout the year but occur more frequently in April–July, and less frequently in September, November, and December. Figure 13 shows time plots of data records with all years folded into one 12-month period. (An explanation of Figure 13 is given under STATION REGRESSION CURVES.) Only one observation per month was used; when duplicate observations were made, usually the one nearest mid-month was used.

In addition to the CalCOFI data, portions of records from five shore stations (surface only) were analyzed:

	Temperature	*Salinity*
Blunts Reef	1955–62	1957–62
S.E. Farallon Island	1955–62	1957–62
La Jolla	1950–62	1956–62[2]
Guadalupe Island	1956–60	—
Cedros Island	1957–62	—

Observations were made daily. The records were collected by the U.S. Coast and Geodetic Survey and Scripps Institution of Oceanography (unpublished). For this analysis, monthly averages (daily observations averaged for each month of each year) were entered as initial data. Thus, there is one value per month comparable in number to the CalCOFI sampling program, but with some high frequency variation filtered out.

CHOICE OF THE 10-METER LEVEL

Hydrographic casts were made during about 80 percent of the station occupations; the remaining 20 percent were "net-haul" stations, where work consisted of biological sampling and a 10-meter temperature and salinity measurement. The 10-meter level was chosen to represent the upper mixed layer in lieu of a surface sample to avoid such transient conditions as might be caused by rain or river runoff and by diurnal heating and cooling. In some places a shallow summer thermocline may develop. When this thermocline is shoaler than 10 meters it is readily subject to wind stirring; hence, its existence is usually brief. These arguments do not obtain in the vicinity of Cabo San Lucas[3] where oceanic fronts and other complex features persist (Griffiths, 1965).

ANALYSIS

An expression of the mean seasonal variation of a characteristic may be obtained from a digital record by Fourier polynomials, a method of harmonic analysis. Because the time intervals between data measurements are irregular, standard textbook formulas derived for processes sampled at equally-spaced intervals are unsuitable and hence an approach from basic concepts is necessary. A detailed description of each data record by harmonic analysis is not necessary; the only harmonics needed are those which contribute significantly to the description of the seasonal variation. This consideration leads to a different but totally equivalent approach which has an added advantage. The mean seasonal variation may be obtained by least squares regression of the data (considering each station record as a time series) to annually periodic sinusoids. Van Vliet and Anderson[4] analysed sea surface temperature records for seasonal variation by fitting annual and semiannual harmonics to the observed data by regression analysis. Their analyses were performed on long records of daily temperature observations at four shore stations and two weathership stations. Least squares regression analyses for curve fitting is identical to the more common application of estimating linear relationships. The added advantage of this method is seen in the statistical approach; it is a natural adjunct of regression analysis to compute measures of dispersion, correlation coefficients, and significance parameters. Though less natural, such computations can be made with truncated Fourier polynomials.

Natural events driven by insolation tend to vary with an annual cycle that may be roughly described by a sinusoid. However, because the effect of insolation is often indirect, the rough approximation provided by the annual sinusoid can usually be refined by

[2] Validity of salinity observations for 1944–55 were questioned by Roden (1961); hence, these observations were not included in this analysis.

[3] Geographical locations are identified in Figure 2.

[4] Statistical analyses of sea surface temperature time series (unpublished manuscript). U.S. Navy Electronics Laboratory, San Diego, Calif.

including the semiannual harmonic.[5] The frequent 3- and 4-month gaps in the data records and the brevity of the records preclude any significant results from the third harmonic.

The general form of the regression curve is:

$$y = A_1 \cos\theta + B_1 \sin\theta + A_2 \cos 2\theta + B_2 \sin 2\theta + C$$

where θ is the angular equivalent of the day of year in radians. In least squares regression the sum of the squares of the data anomalies from the regression curve,

$$\sum_i [y_i - (A_1 \cos\theta_i + B_1 \sin\theta_i + A_2 \cos 2\theta_i + B_2 \sin 2\theta_i + C)]^2,$$

is minimized with respect to each of the five coefficients where,

$$y_i = \text{data values indexed to } \theta_i$$

$$\theta_i = \frac{2\pi[(\text{month} - 1)\ 30 + \text{day}]}{360}$$

The resulting set of equations is solved simultaneously for the coefficients. The same coefficient formulas can be derived from the Fourier polynomial approach. When equal intervals are assumed (integral division of year) the formulas simplify to the standard textbook formulas for Fourier polynomial coefficients.

From the station regression curves were derived the long term mean (13-year), extreme values, and range. Statistics describing the data and the fit of the regression curve were computed by standard formulas. These statistics include standard deviation, standard error of estimate, coefficient of correlation, and the F-ratio test (null hypothesis: the mean provides as adequate a fit to the data as the regression curve). The coefficient of correlation refers to the correlation of the characteristic with time of year.

DISTRIBUTION OF THE 13-YEAR MEANS

The long term (13-year) mean of temperature (Figure 3) shows the influence of currents and upwelling. The mean temperature ranges from 12° C. near San Francisco to 24° C. near Cabo San Lucas. More than half the range (less than 18° C. to 24° C.) falls between Punta Eugenia and Cabo San Lucas, one-third of the total distance. The isotherms tend to parallel the coast along northern and central California with the colder water inshore, whereas the isotherms are nearly perpendicular to the shore along the southern part of Baja California. The colder inshore water along northern and central California is a mixture of cold waters from the North Pacific Current and cold waters upwelled along the coast. A second important upwelling region, indicated by a 16° C. isotherm, is near the coast immediately north of the United States-Mexican border and extending southward along northern Baja California. West of this upwelling region is a warm tongue-like feature extending into the island area off southern California.

[5] Van Vliet and Anderson performed an autocorrelation analysis on the long records (7–40 years) of daily temperature observations and showed the semiannual harmonic contains a significant portion of the energy of seasonal variation in four of their six stations.

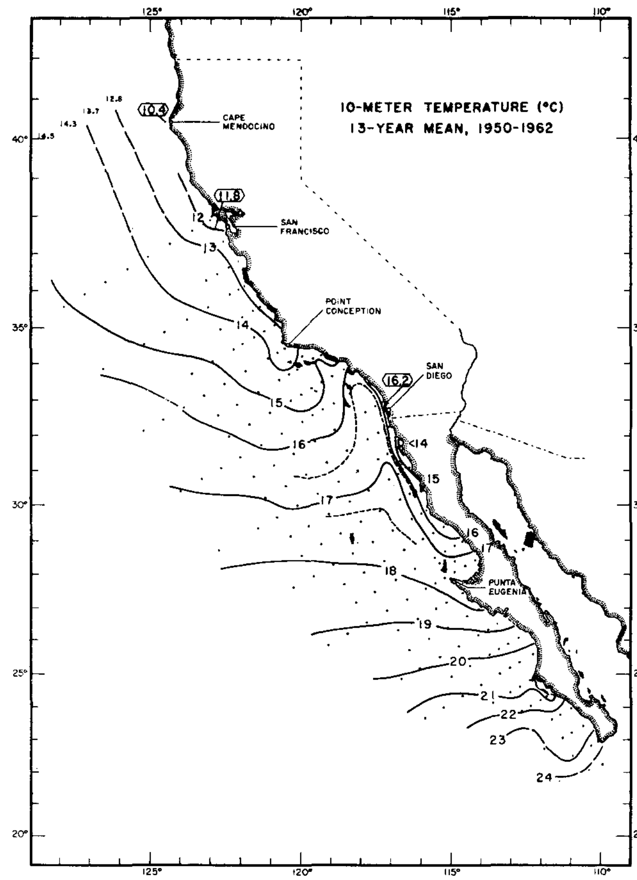

FIGURE 3. Ten-meter temperature (°C); 13-year mean, 1950–62. Interval: 1° C. In this and other figures thin, short-dashed lines show half intervals and thick, long dashes show continuation of standard-interval isopleths into regions of infrequent sampling. Boxed values refer to shore stations.

The long term mean salinity (Figure 4) ranges from less than 33.0‰ near Cape Mendocino to greater than 34.6‰ near Cape San Lucas. More than half this range is along southern Baja California. The largest gradients are in the southernmost portion of the CalCOFI area and in the upwelling region north of Point Conception. A low-salinity tongue, characteristic of the California Current, lies approximately 240 miles from and parallel to the northern California coast. The displacement of the low-salinity tongue farther offshore from the low-temperature tongue is evidently the consequence of the mixing of upwelled water, characteristically cold with high salinity, and California Current water, characteristically cold with low salinity. Along southern California and northern Baja California is a body of water with a nearly uniform mean salinity, 33.55‰ ± 0.05‰ and a small standard deviation, approximately ± 0.15‰. This area shows a complex distribution of mean temperature.

Reid, Schwartzlose, and Brown (1963) described a shoreward movement of water near latitude 31° N. to 32° N. Features in the 33.4‰ and 33.5‰ isohalines probably relate to this flow, as perhaps does the

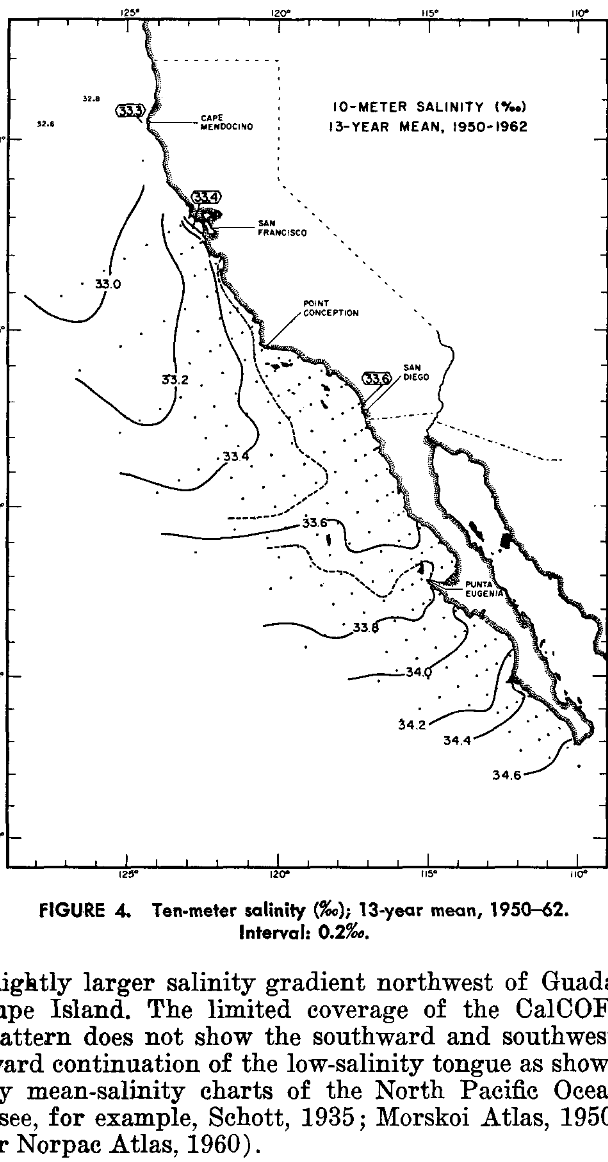

FIGURE 4. Ten-meter salinity (‰); 13-year mean, 1950–62. Interval: 0.2‰.

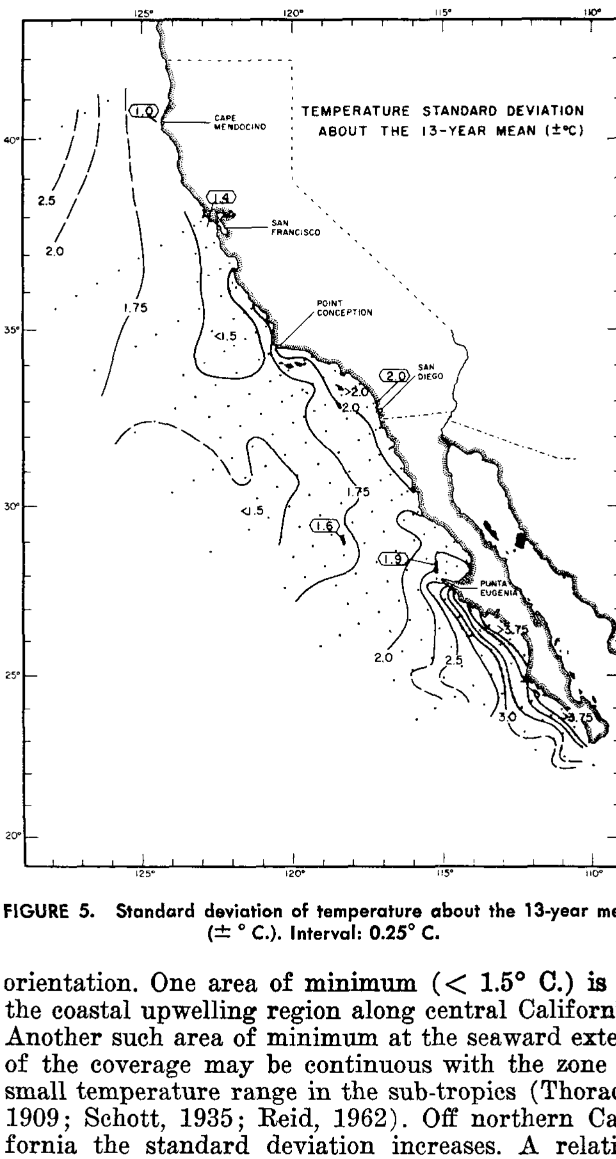

FIGURE 5. Standard deviation of temperature about the 13-year mean (± ° C.). Interval: 0.25° C.

slightly larger salinity gradient northwest of Guadalupe Island. The limited coverage of the CalCOFI pattern does not show the southward and southwestward continuation of the low-salinity tongue as shown by mean-salinity charts of the North Pacific Ocean (see, for example, Schott, 1935; Morskoi Atlas, 1950; or Norpac Atlas, 1960).

The results of analyses at shore stations are shown as boxed numbers on these and other distribution charts. The mean temperatures at the Guadalupe Island and Cedros Island Stations are 0.5° C. greater than at the adjacent stations. In both cases the records covered only half of the 13-year period. When neighboring CalCOFI stations were analyzed with equally truncated records no differences could be found in the means. Thus, temperature regression values for the two island stations are misleading and are not given.

STANDARD DEVIATION ABOUT THE MEAN

The distributions of standard deviation about the 13-year means appear in Figures 5 and 6. This measure of dispersion combines the seasonal and nonseasonal influences.

The chart of standard deviations for temperature shows a band of small dispersion, less than 1.75° C., extending across the CalCOFI region in a meridional orientation. One area of minimum (< 1.5° C.) is in the coastal upwelling region along central California. Another such area of minimum at the seaward extent of the coverage may be continuous with the zone of small temperature range in the sub-tropics (Thorade, 1909; Schott, 1935; Reid, 1962). Off northern California the standard deviation increases. A relative maximum (> 2.0° C.) occurs along the southern California-Baja California coast. There is a coastal high south of Punta Eugenia having values greater than 3.75° C.

The chart of standard deviations for salinity shows a coastal maximum (> 0.3‰) in the vicinity of San Francisco Bay, and a decrease seaward and southward (to < 0.15‰). The seaward minimum in standard deviation connects with the coastal minimum of the mid-CalCOFI region within the 0.175‰ contour. The body of water with nearly uniform salinity of 33.55‰ off southern California has a very small standard deviation. A maximum occurs near Guadalupe Island which is in a location immediately south of a large salinity gradient to be seen in the distribution of mean salinity. The area of greatest standard deviation (0.35‰) is centered 70 miles offshore from southern Baja California.

The distribution of standard deviations for salinity has a general relation with the gradient of mean

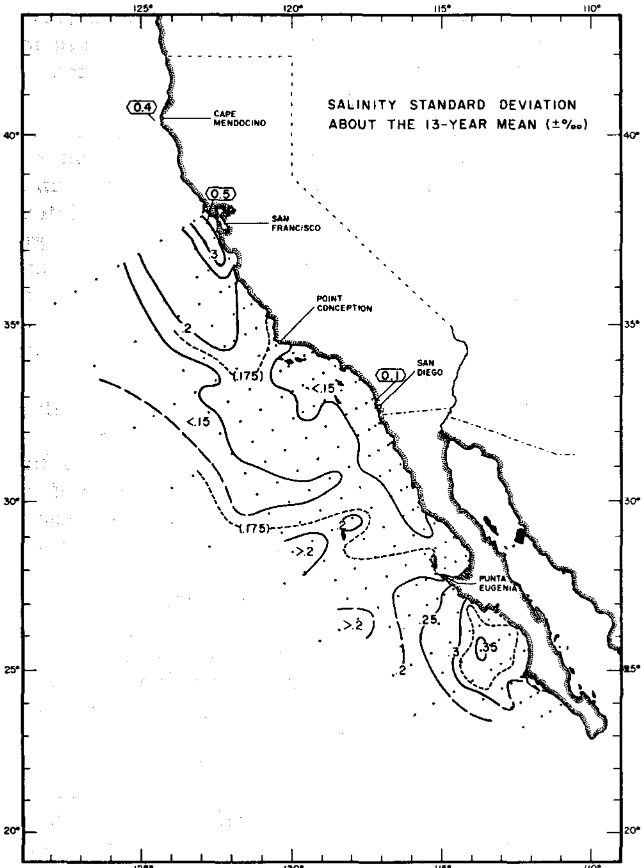

FIGURE 6. Standard deviation of salinity about the 13-year mean (±‰). Interval: 0.05‰.

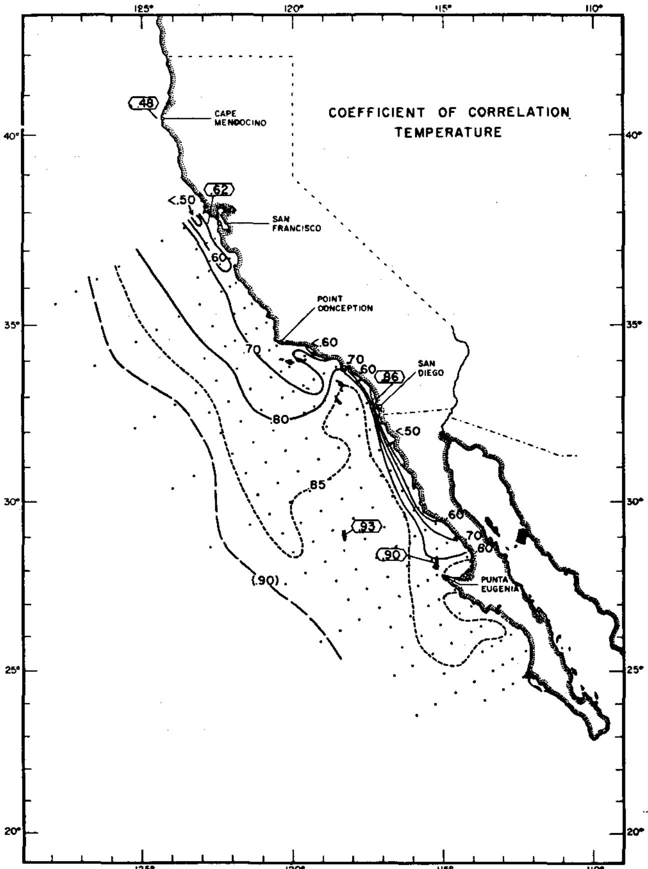

FIGURE 7. Coefficient of correlation for temperature. Interval: 0.1.

distribution. Areas of large gradient coincide with areas of large dispersion, and areas of small gradient with areas of small dispersion. This circumstance probably results from a large ratio of nonseasonal (random) to seasonal variation in the salinity record. The increase in standard deviation near the western edge of the CalCOFI region is not well established but it corresponds to relatively large salinity gradients seen in charts for the North Pacific Ocean.

COEFFICIENT OF CORRELATION AND MEAN RANGE: TEMPERATURE

The coefficients of correlation for temperature and salinity are measures of the degree of relation between the characteristics and time of year.[6]

The correlation of temperature with time of year (Figure 7) has a coefficient greater than 0.80 over the greater portion of the CalCOFI region. The coefficient is greater than 0.85 along the western extent and in the southern half including the coastal region along southern Baja California. Coefficients are smaller in the upwelling regions—in a broad band along central California and in a narrow band from Point Vincente to Bahia de Sebastian Vizcaino. Small coefficients are caused either by large total variance, consequent on the sporadic nature of upwelling, or by small explained variance that results when effects of upwelling are out of phase with the solar heating-cooling cycle dominant elsewhere. A mixture of these effects is probable.

The F-ratio test [7] was applied to the regression of the annual harmonic only.[8] Where the null hypothesis is rejected at the 2.5 percent significance level the seasonal variation may be considered significant. The seasonal variation of temperature is everywhere significant.

An additional test, attributed to Stumph by Conrad and Pollak (1950), was applied to 12 representative stations. The probability p that an amplitude A might have been obtained by harmonic analysis of a particular set of random numbers is given by:

$$p = \exp \frac{-A^2}{n^{1/2} \sum_{i=1}^{n} a^2_i}$$

[6] $R = \left(\frac{\text{variance explained by regression curve}}{\text{total variance}}\right)^{1/2}$ where R is the coefficient of correlation.

[7] $F = \left(\frac{\text{explained variance}}{\text{unexplained variance}}\right)$ weighted by degrees of freedom. The degrees of freedom are determined by the number of variables in the regression equation and the sampling frequency.

[8] Van Vliet and Anderson found by the F-ratio test that the semiannual harmonic significantly increases the explained variance in five of their six stations. Application of this test to the semiannual harmonics of the CalCOFI records is marginal in value because the number of data in each record is small.

where *ai* is the amplitude computed from the *ith* cycle of the period concerned and *n* is the number of intervals of this period in the series. At all stations tested the probability computed with the annual harmonic of temperature is inconsequential (Table 1).

The distribution of temperature range, maximum of regression curve less minimum (Figure 8), closely reflects the distribution of standard deviation. The major exception is in the region of low correlation

TABLE 1

PROBABILITY THAT AN AMPLITUDE (ANNUAL HARMONIC) AS GREAT AS THAT CALCULATED MIGHT HAVE BEEN OBTAINED BY HARMONIC ANALYSIS OF PARTICULAR SET OF RANDOM NUMBERS

Station	Temperature	Salinity
60.60	0.01	0.17
60.80	0.01	0.84
73.60	2×10^{-3}	0.39
80.51	1×10^{-3}	3×10^{-3}
80.55	2×10^{-4}	0.02
80.70	3×10^{-5}	7×10^{-4}
80.90	1×10^{-4}	0.22
90.37	7×10^{-6}	4×10^{-4}
90.70	3×10^{-5}	0.03
107.32	2×10^{-3}	5×10^{-3}
107.35	8×10^{-5}	0.88
107.50	4×10^{-5}	2×10^{-4}

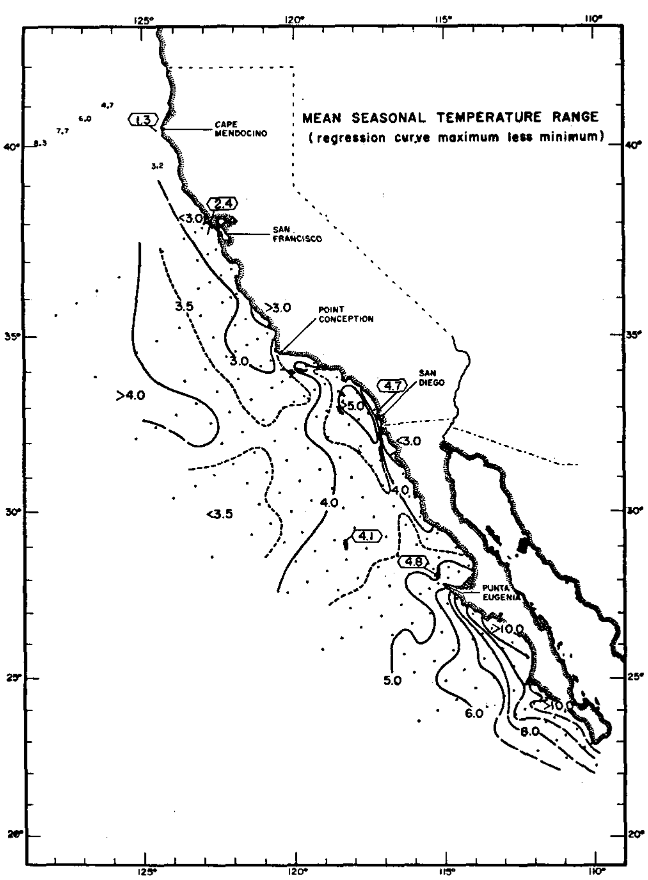

FIGURE 8. Mean seasonal temperature range which is defined as the regression curve maximum less the minimum. Interval: 1° C.

along the coast of southern California-northern Baja California. Here the standard deviation increases to the coast, whereas the seasonal range reaches a maximum 20 to 40 miles offshore.

Temperature range is less than 3.0 °C. in the northern California upwelling region. The band of small range is defined by the 3.5° C. isotherms, and has flanking areas greater than 4.0° C. The isolated area with range greater than 5.0° C. off San Diego coincides with the warm tongue seen in the mean distribution. Temperature range exceeds 5.0 °C. in Bahia de Sebastian Vizcaino and south of Punta Eugenia, increasing to greater than 10.0 °C. along the coast of southern Baja California.

The chart of temperature range is grossly similar to range charts of the North Pacific Ocean (e.g. Reid, 1962). Considerable detail has been added by the present analysis. Robinson (1957) prepared a chart of surface-temperature range for the northeastern Pacific Ocean from a comprehensive study of bathythermograph records (and of some serial hydrographic data). Her chart (her Figure 44) overlaps the present coverage north of 35° N. latitude and shows the band of small range displaced offshore at the latitude of San Francisco. Her values are generally greater by 1.5° C. to 2.0 °C. Closer examination has revealed that most of the differences between the range charts are caused by differences in the determination of the seasonal temperature maxima. During the period of heat gain in the region where the coverage of the charts overlap the temperature of the surface layer may occasionally exceed that at 10 meters by more than 1° C. This difference may result from warming of newly upwelled water or warming of water with shallow density stratification caused by river and bay effluent.

Wyrtki (1964) prepared a chart of surface-temperature range for the eastern Pacific Ocean, 30° N. to 40° S. His chart is similar except in a narrow band along southern Baja California. In this region he did not find the range to exceed 7° C. The present analysis finds lower temperatures at the temperature minimum.

COEFFICIENT OF CORRELATION AND MEAN RANGE: SALINITY

The correlation coefficient for salinity (Figure 9) ranges from nominally zero to slightly greater than 0.70. There is a series of lobes having coefficients greater than 0.40. Only off southern Baja California are there any values greater than 0.60. The generally low values indicate that the nonseasonal variations dominate much of the salinity record.

The shaded areas show where the null hypothesis of the F-ratio is rejected at the 2.5-percent significance level. These areas of significant seasonal variation usually coincide with the areas having correlation coefficients greater than 0.40. The exception to this observation occurs north of 34° N. latitude where the sampling was less frequent. The probability com-

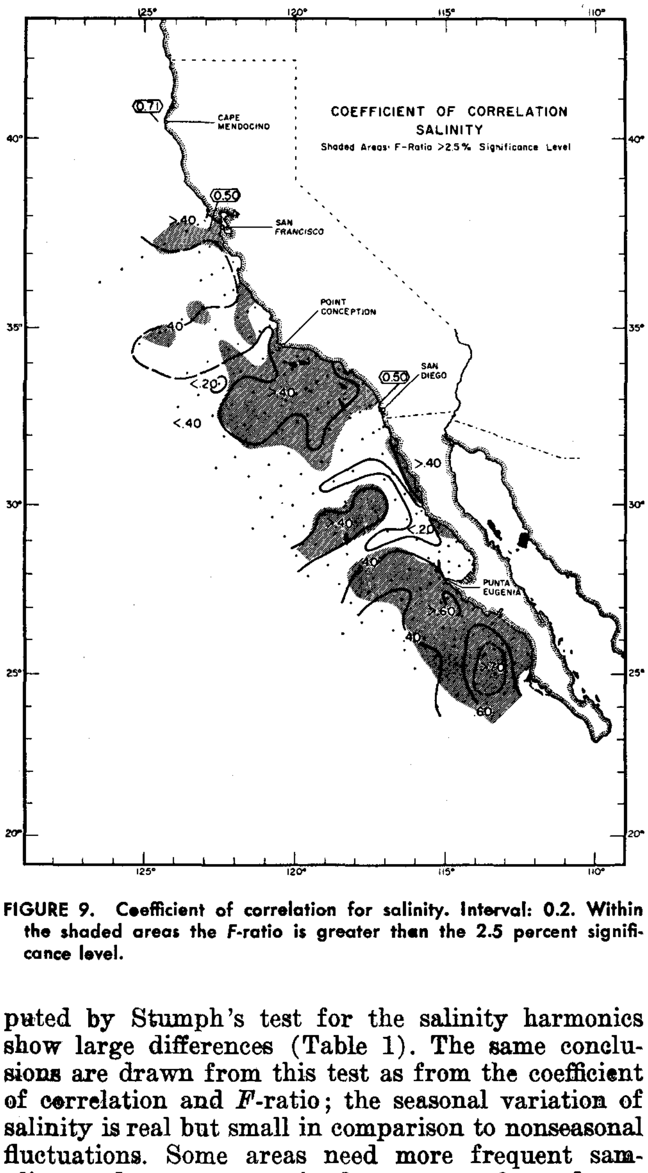

FIGURE 9. Coefficient of correlation for salinity. Interval: 0.2. Within the shaded areas the F-ratio is greater than the 2.5 percent significance level.

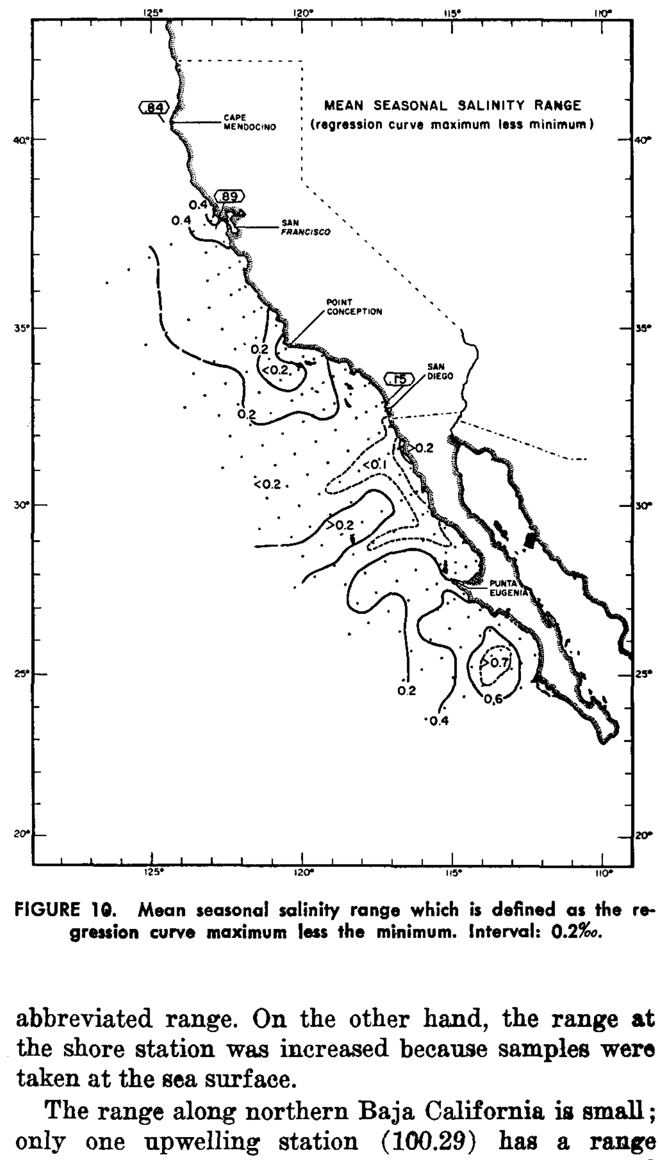

FIGURE 10. Mean seasonal salinity range which is defined as the regression curve maximum less the minimum. Interval: 0.2‰.

puted by Stumph's test for the salinity harmonics show large differences (Table 1). The same conclusions are drawn from this test as from the coefficient of correlation and F-ratio; the seasonal variation of salinity is real but small in comparison to nonseasonal fluctuations. Some areas need more frequent sampling to demonstrate a signficant seasonal trend.

The distribution of the range of mean salinity (maximum of regression curve less minimum, Figure 10), reflects that of correlation coefficient and standard deviation, especially the former. Three major regions have a range greater than 0.2‰; two of them have ranges greater than 0.4‰. The maximum range contour, 0.7‰, is centered 100 miles offshore from southern Baja California. This maximum contains most of the stations which have a range equivalent to two standard deviations or more. The other region of range greater than 0.4‰ is found near San Francisco Bay. The shore station at S.E. Farallon Island which includes data for only 5 years, 1957–62, has a range of 0.9‰. This station exhibits an abrupt minimum in March coinciding with the peak discharges of the Sacramento and San Joaquin Rivers. The nearby CalCOFI stations were infrequently sampled in this month and thus may have produced an abbreviated range. On the other hand, the range at the shore station was increased because samples were taken at the sea surface.

The range along northern Baja California is small; only one upwelling station (100.29) has a range greater than 0.2‰. Twenty miles offshore is a band of especially small salinity range. This band also displays an extremely small coefficient of correlation.

SHORE STATIONS

Some of the results of the analyses of data from shore stations are similar to those for local hydrographic stations. Results for Blunt's Reef station appear to be consistent with an extrapolation of more southerly results. The temperature analysis at S.E. Farallon Island is identical to that of neighboring CalCOFI stations. The salinity analysis for the same station (only 5 years of record) gave greater deviation, range, and correlation. The other shore stations have slightly smaller deviations and greater correlation coefficients than neighboring CalCOFI stations. These results may be caused by the filtering process of using monthly averages as shore station input data. The ranges did not differ among these stations.

REGRESSION CURVE EXTREMES

The extremes of the station regression curves and their months of occurrence are shown in contoured charts (Figures 11 and 12). The seasonal temperature minimum occurs in March over most of the oceans in the northern hemisphere temperate zone. The seasonal maximum occurs in September. The timing of the variation is altered near the coast in the CalCOFI area. In regions of upwelling and regions influenced by upwelled waters the minimum occurs late, usually in April and May. Off southern Baja California the late temperature minimum extends beyond the offshore influence of the coastal upwelling. In this latter region the anomaly in phasing of the temperature variation appears to result from seasonal variation in advection. A region off southern California has an early temperature minimum. The scale and location of this region offer evidence that the phase lead is caused by the pattern of the local currents. The seasonal temperature maximum occurs earliest (August) in a limited area off southern California. The coastal upwelling region of central California experiences its maximum temperature as late as the end of November. The maximum is slightly late at a few prominent upwelling stations along the Baja California coast.

Because the seasonal variation of salinity is considerably less regular than that of the temperature (at some stations the variation is not significant) the distribution of extreme dates is not as definitive as those for temperature. A general pattern is evident, however. Where the seasonal variation is significant seaward of the upwelling regions the salinity minimum is in spring and the maximum in fall. This timing agrees with the seasonal variation of advection and its probable effect on the distribution of mean salinity. In the upwelling regions along central California the maximum salinity is in summer, shortly after the minimum temperature is attained. The minimum salinity usually occurs in winter. The salinity extreme in the upwelling region along northern Baja California occurs earlier than for the region farther north. The salinity maximum along southern Baja California occurs in fall along with the countercurrent.

STATION REGRESSION CURVES

The complete data records and station regression curves for five representative stations are plotted in Figure 13. The dashed lines are drawn at plus and minus one standard error of estimate of the characteristic from the regression curve.

Station 70.52 is in the upwelling region, 6 miles from the shore and immediately south of Monterey Bay.[9] At this station the correlation coefficients are low and standard errors of estimate are large. Data are scarce for the winter months. The dispersion of the salinity values is particularly large at the beginning of the upwelling season, April and May. The upwelling season along northern and central California is characterized by the low temperatures in spring and summer with accompanying high salinities. Sometimes the temperature and salinity anomalies show an inverse relation. In particular, the highest and lowest salinities for April have as their corresponding temperature observations the lowest and highest April temperatures, respectively.

Station 70.70 is 80 miles farther offshore. The temperature variation has a greater correlation coefficient, and a lesser standard error of estimate than at the nearshore station. The salinity record shows a poorer correlation and greater standard error of estimate. The offshore salinity variation is very different; its minimum is in spring. The very large positive temperature anomaly and negative salinity anomaly were observed in June 1958. The observations of this anomalous water show that its extent was limited (CalCOFI Atlas No. 1).

These two stations show the large standard error of estimate relative to the moderate ranges in seasonal variation that typifies the surface water in the CalCOFI area north of the latitude of Point Conception. The regression analysis of salinity is of marginal significance. The *F*-ratio test indicates that the regression curves of these example stations provide a better estimate of the salinity than the mean, although the regression curves of some neighboring stations are not significant. Stumph's test (calculated for neighboring stations but not for these particular stations) indicates that the salinity variation within each year may differ considerably from the mean regression curve.

Nonsignificant results from a regression analysis may be a direct result of a low sampling frequency. The stations off central California have moderate to poor sampling frequency and an uneven distribution of data within each year.

The regression curve and record of temperature for station 93.50 and similarly of salinity for station 87.50 also appear in Figure 13. Both stations are off southern California. The standard errors of estimate of the regression curves are small. The range of the salinity curve is moderate, having the same value as the spread of one standard error of estimate above and below the curve. Thus the correlation is moderate. The salinity curve is similar to that for the upwelling station, 70.52. Station 87.50 is just north of San Nicolas Island and over the submarine ridge of which San Nicolas is a part. The depth at this station is 73 meters. The corresponding temperature curve is similar to that of station 93.50 but has a lesser range and poorer correlation, 3.2° C and 0.67, respectively.

The late temperature minimum shown in the curve for 93.50 also appears in a few neighboring stations, all of which are downstream of the cold upwelled water added to the California Current at Point Conception and north. The corresponding salinity curve

[9] The data plotted for station 70.52 were actually obtained at three stations, 70.51, 70.52, and 70.53 with an interval of 4 miles between 70.52 and the others. With one exception no two stations were occupied during the same cruise. The short distance between the stations was considered to be of minor consequence as compared to the month-to-month changes of temperature and salinity in the locale of the stations. Therefore, the data were combined as if observed at one station. Data were similarly combined at several other coastal CalCOFI stations.

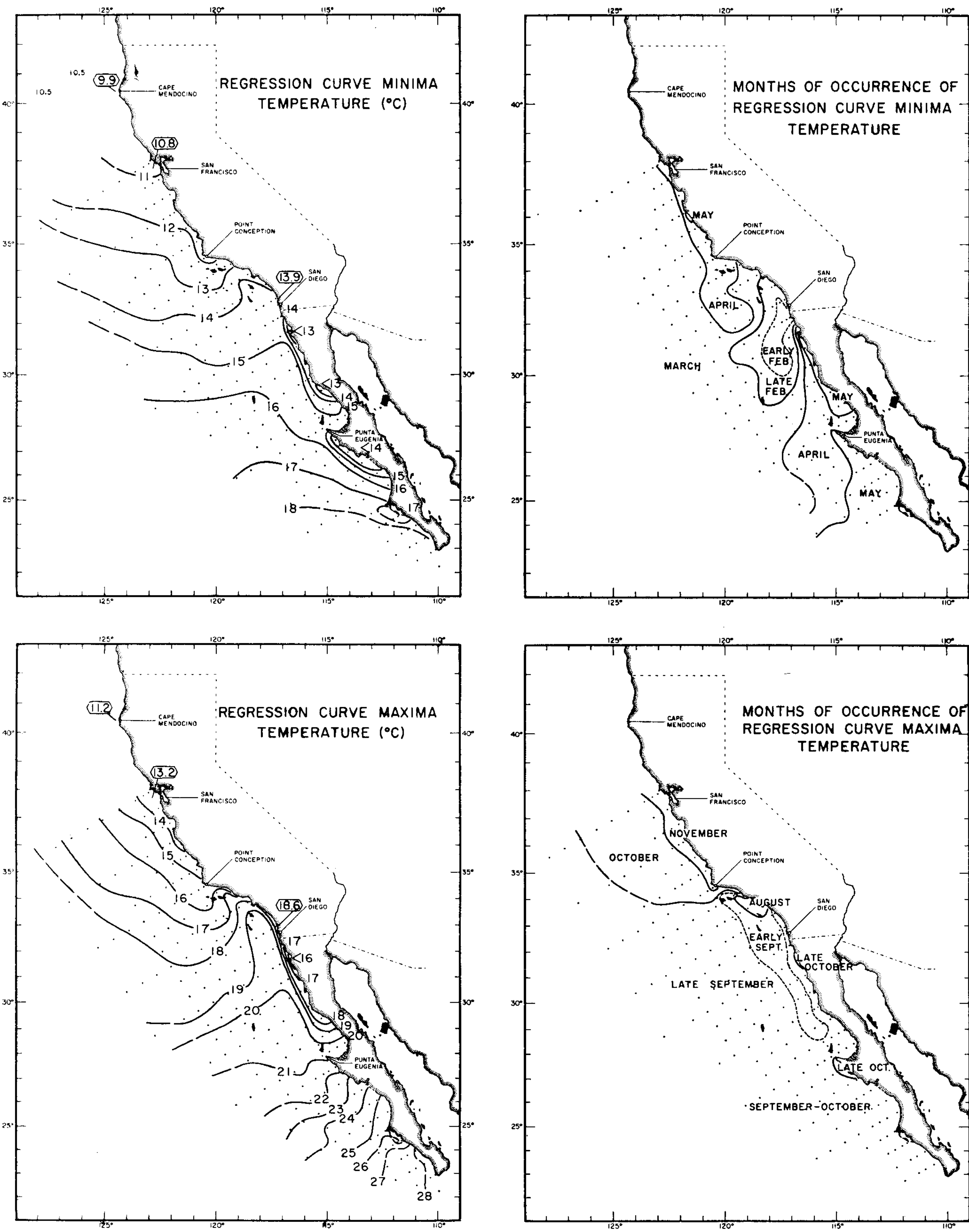

FIGURE 11. Extremes of temperature regression curves and corresponding months of occurrence.

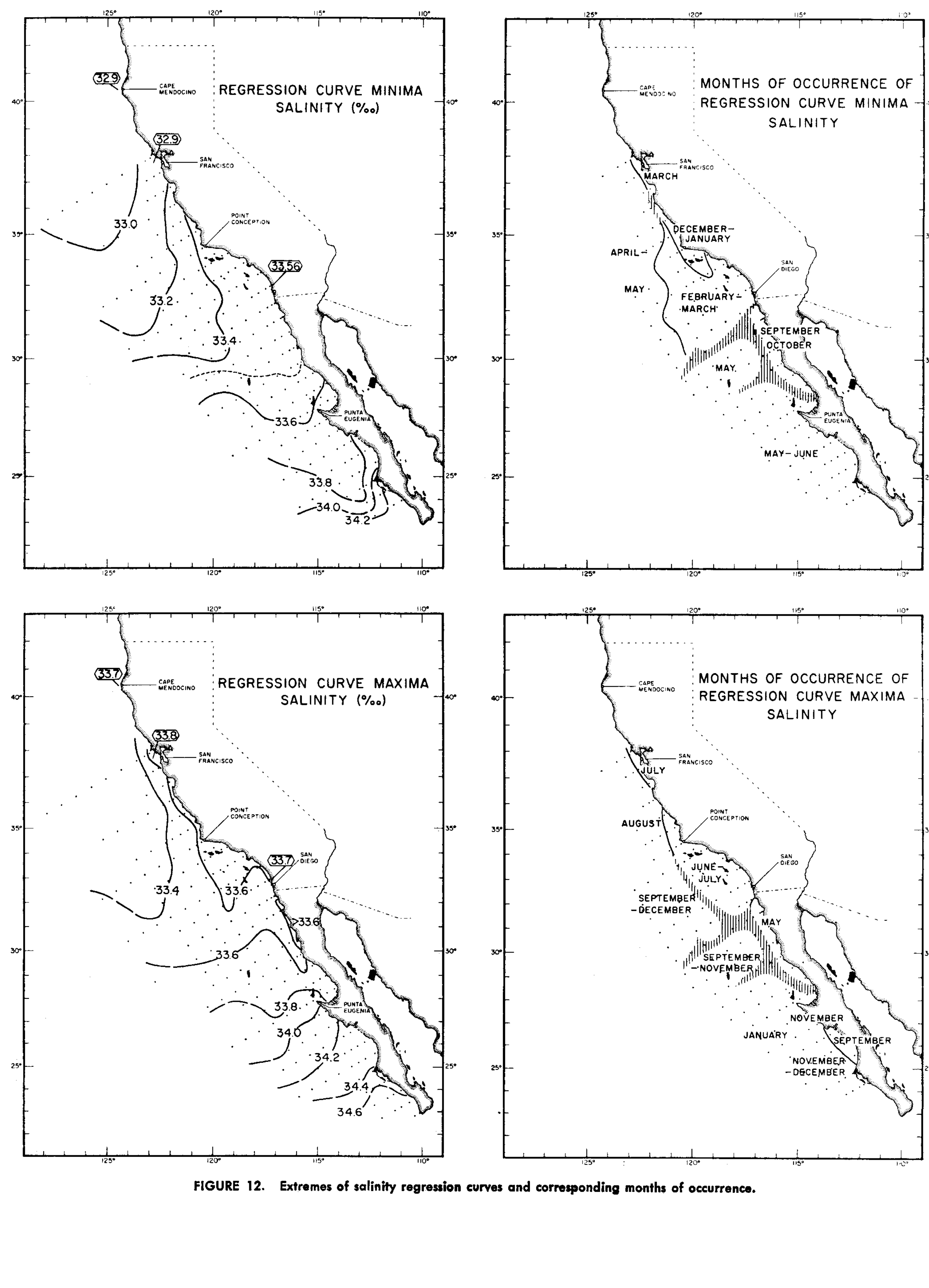

FIGURE 12. Extremes of salinity regression curves and corresponding months of occurrence.

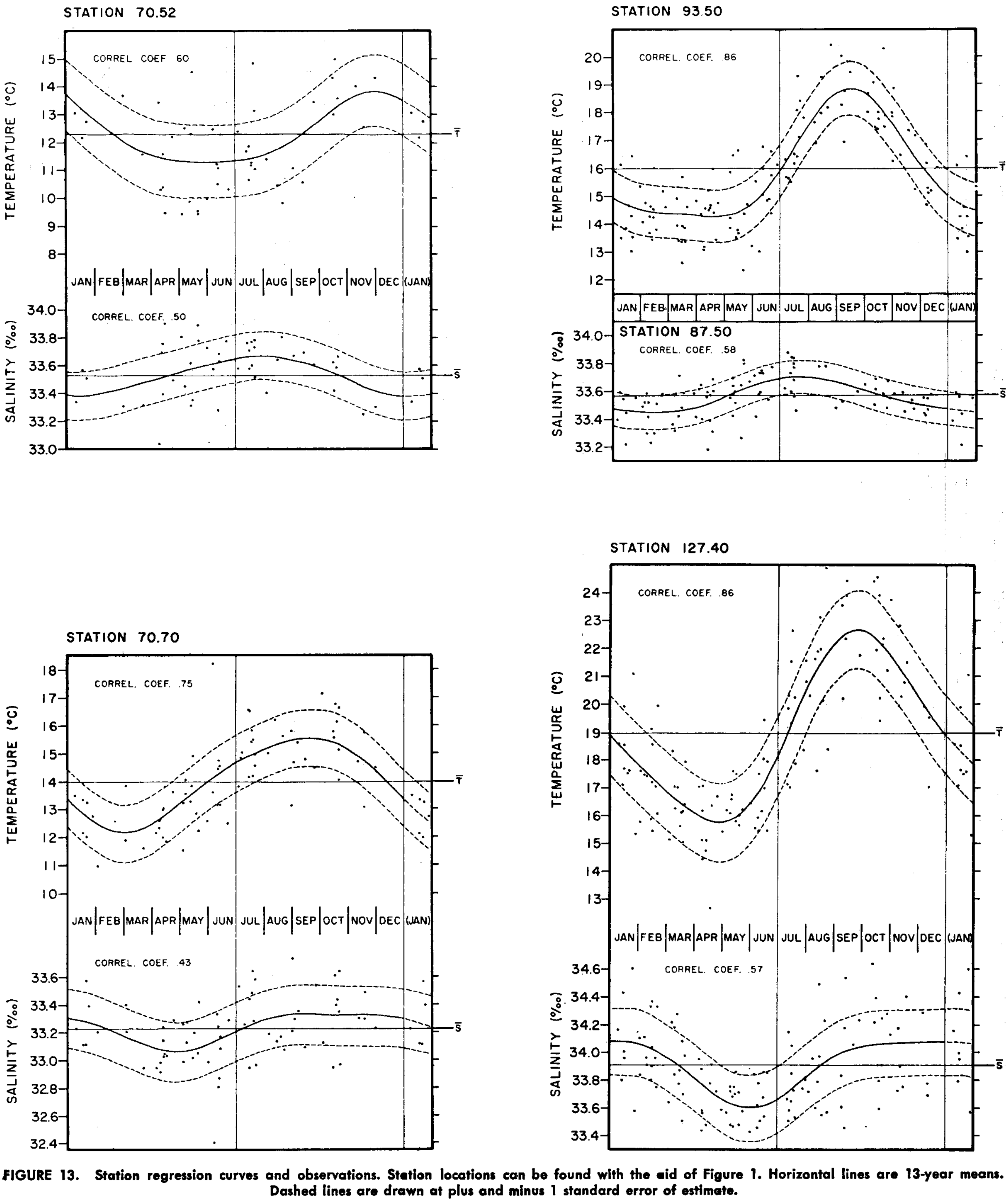

FIGURE 13. Station regression curves and observations. Station locations can be found with the aid of Figure 1. Horizontal lines are 13-year means. Dashed lines are drawn at plus and minus 1 standard error of estimate.

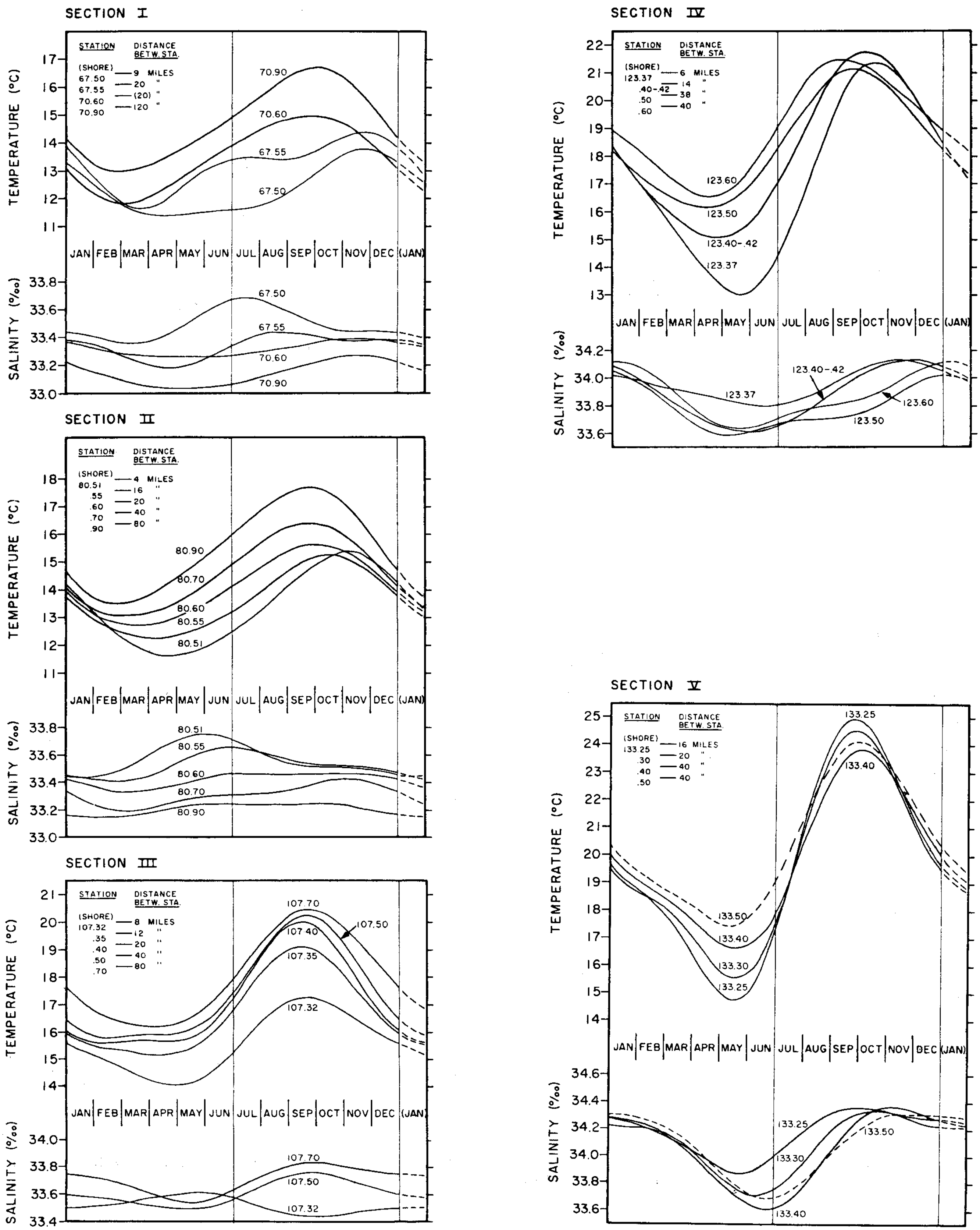

FIGURE 14. Station curves of seasonal variation of temperature and salinity grouped from lines perpendicular to the coast and labeled as sections. Sections locations are shown on Figure 2.

for 93.50 has a very small range and poor correlation, 0.17‰ and 0.33.

The temperature curve for station 127.40, off southern Baja California, has a 50-percent greater range than that for station 93.50, and a 50-percent greater standard error of estimate. These effects cancel to produce the identical correlation coefficient. The range of the salinity curve and its standard error of estimate are each greater by a factor of two than those for station 87.50; thus it also has the same correlation coefficient. At station 127.40 the seasonal temperature minimum is in late April and the seasonal salinity minimum in May. This aspect indicates an influence by some seasonal variation in circulation.

Station regression curves fall into regional patterns. Meaningful pattern variations occur perpendicular to the coast. Figure 14 gives station regression curves superimposed upon one another for easy visual comparison. For each graph, four or five stations were chosen that constituted a line section across the current and perpendicular to the coast. The locations of the line sections are shown as dashed lines in Figure 2. The jog in section I which includes stations from lines 67 and 70 was made to show typical station curves from stations that are well sampled. The distance between neighboring stations is given to provide the correct perspective of offshore temperature and salinity gradients. A time scale that is common to the temperature and salinity curves allows visual comparison of the variation of these characteristics.

As its temperature and salinity curves show, station 67.50 of section I is in an upwelling region. Station 67.55, 20 miles farther offshore, is similar to the offshore regime during the initial part of the upwelling season, but by midsummer the temperature curve responds to the effects of upwelling. The form of the corresponding salinity curve is also intermediate between those for the offshore and upwelling regimes.

Station 80.51, section II, near Point Conception does not maintain its low temperature as long as upwelling stations farther north. The slightly higher temperature at 80.51 than offshore in December and January may be caused by the winter countercurrent sometimes found along the coast.

The offshore temperature gradient along section III increases after the minimum temperature is reached and is largest at the time of the maximum temperature. Thus, the temperature gradient, but not the value of temperature, may indicate continued upwelling through September. Initial upwelling (station 107.32) brings high-salinity water to the surface. The salinity minimum follows the maximum by 4 or 5 months and coincides with the large temperature gradient. The salinity distribution charts for 10 meters (following text) for August through December reveal isolated low-salinity water in the upwelling region along the northern Baja California coast. This low-salinity water which replaces the isolated high-salinity water of May and June has its source in the salinity-minimum layer of the thermocline. The salinity minimum was described by Reid, Roden, and Wyllie (1958) and was the subject of a paper by Reid, Worrall, and Coughran (1964). These authors ascribed the minimum to freer horizontal mixing of the surface waters than of the thermocline water; the higher salinities of the west mix laterally into the surface water of the California Current more readily than into the thermocline layer. A study of data of CalCOFI hydrographic stations reveals that the salinity minimum which approximately corresponds to the 300 cl/ton thermosteric anomaly[10] surface extends to the coast in the latter half of the year. The higher salinity water upwelled in spring comes from a denser source. Thus, as the temperature gradients indicate, the upwelling may persist from spring through fall. Upwelling brings high-salinity water to the surface layers in spring and low-salinity water in fall. Though the offshore temperature gradient is maintained in this period the temperature goes from its seasonal minimum to its maximum.

Offshore, along section III, the salinity changes have phasing opposite to that of the nearshore regime in response to advection changes. In the intermediate region the opposing effects cancel and here no variation of salinity is found. This region has especially low correlation coefficient and range (Figures 9 and 10).

In surface distribution charts, station 123.37, section IV, appears to be the dominant upwelling station along a section of coast where the scope of upwelling is limited. The largest offshore temperature gradient occurs in late June, 2 months after the minimum temperature. Along station line 133, section V, the offshore gradient is largest at the time of the temperature minimum and an onshore gradient occurs at the maximum. Along both station lines the salinity minimum nearly coincides with the temperature minimum as in the offshore regions farther north. At this time an onshore salinity gradient is evident, perhaps produced by upwelling. Beginning in September, the four salinity curves of station line 123 fall into two groups, probably the result of a cyclonic eddy centered between stations 123.42 and 123.50 and the countercurrent.

DISTRIBUTIONS OF MONTHLY MEAN TEMPERATURE

Charts of mean temperature for each month were constructed from the curves of seasonal variation by digitizing the regression curves at midmonths (charts follow text). Smoothing of the contours was performed in the manner that gave greater emphasis to values at those stations which had relatively more frequent sampling (Figure 2). The stations offshore and south of Cabo San Lazaro were sampled infrequently during some seasons. In such situations, where the regression curve can only provide a tenuous

[10] Montgomery and Wooster (1954). Approximately equivalent to the 24.97σt surface.

interpolation, the values were excluded from the charts. Where the contours as drawn violate the given value, that value is shown in parentheses.

The seasonal variation of temperature off northern California can be characterized by noting the various positions of the 12° isotherm in the monthly charts. The broadest extent of water with temperatures less than 12 degrees occurs in March. Subsequent monthly charts show the development of a band of such cool water along the coast south to Point Conception. The 12-degree isotherm begins its retreat to the north in June and is not found in the last 3 months of the year. The maximum offshore temperature gradient from this cold upwelled water is in August.

The March temperature chart shows the tongue of warm water in the island area off southern California. This feature, which develops in prominence in subsequent months, occurs in the region of early (February) temperature minimum (Figure 11). It is produced from local differences in advection in conjunction with coastal upwelling (Reid, Roden, and Wyllie, 1958). The offshore waters are readily replenished with cold waters from the north whereas nearer shore the slower moving waters respond to the local heating. The coastal upwelling of deep cool waters causes the warmed nearshore waters to assume the tongue-like pattern. This feature appears in 10 of the monthly charts; the exceptions are January and February. Its greatest development comes in late spring and summer when the southern California eddy is reestablished.

The July and August charts both show an isolated warm region off San Diego. The separation of this region from the main body of water with the same temperature is significant and can be explained by the current flow. A northeasterly flow feeds water into the southern California eddy. Part of the northeasterly flow branches off to turn southeast along the coast of Baja California. The branching coincides with the center of the isolated warm region. At such a division the flow is sluggish. Along the northern Baja California coast the flow is relatively swifter and mixes with the upwelled water. This difference in rate of advection in conjunction with a net heat gain and the inclusion of upwelled waters produces the separation of warm waters. The isolated high-temperature region occurs in other months, though weakly, and would be revealed with a finer scale of contour interval.

In summer there is a 6° temperature difference between the warm waters off southern California, in the vicinity of Santa Catalina Island and the waters off Point Conception, approximately 120 miles distant. In winter the difference is less than 1°.

Upwelling along northern Baja California, as revealed by the temperature field, may occur throughout the year. Upwelling of cold waters is clearly characteristic of April through October; however, coastal temperatures remain less than offshore values throughout the winter. The temperature distribution for individual CalCOFI cruises (CalCOFI Atlas No. 1) support this conclusion as to mean conditions. Small pockets of cold water are found along this coast in many winters. Because there is usually no seasonal countercurrent along northern Baja California, as is found elsewhere, the mass distribution associated with geostrophic balance (for a southerly flow) provides the tendency for lower inshore temperatures at 10-meters throughout the year. Along this section of coast the lowest temperatures occur in April, May, and June, and the largest offshore gradient occurs in July, August, and September. The temperature values at one station (100.29) near Punta Banda require an additional isotherm in seven of the monthly charts.

The upwelling south of Punta Eugenia is centered about station 123.37. The minimum temperatures again are in April through June, but the largest temperature gradient is in June and July. Upwelling ceases before September and does not resume until April. During the upwelling season the isotherms are nearly parallel to the coastline. By September the isotherms have swept northward and are nearly perpendicular to the coastline. During this change considerable warming takes place. In addition to *in situ* heating, an influx of more southerly warmer waters is suggested by the configuration of the isotherms. This influx also appears in the mean salinity distributions discussed later.

The data from the few cruises that extended to the southern tip of Baja California in the upwelling season indicate that a pattern similar to that seen off Punta Eugenia may exist off Cabo San Lazaro. The coolest water is found at station 143.26.

Whereas the distribution of mean temperature in the upwelling regions appears as smooth isotherms, the distributions for individual cruises—especially those with very close station spacing—show that the cold water appears as pockets and tongues. It is probable that higher frequency sampling of a denser pattern of stations would reveal a complex but significant distribution of mean temperature having recurrent upwelling pockets associated with coastal configuration, shelf topography, and local variations in wind stress. That the mean characteristics of a few nearshore stations define large and significant gradients supports this idea.

DISTRIBUTIONS OF MONTHLY MEAN SALINITY

Low-salinity water enters the CalCOFI region from the northwest. On the basis of the limited sampling available water of salinity less than 33.0‰ appears to be in or near the CalCOFI region throughout the year. There is little apparent seasonal variation of salinity in the low-salinity water, $<$ 33.4‰, with the exceptions of the southeastward projecting tongue of water defined by the 33.4‰ isohaline, and the coastal upwelling regions. The tongue of low-salinity water extends farther to the southwest in spring than in fall and, hence, its position correlates with the strength of the California Current. The coastal regime is complex and some difficulty results from the station spacing and sampling frequency. The station regression curves for stations near San Francisco Bay show marginal significance. The low-salinity effluent from the bay is greatest in the spring coincident with upwelling of high-salinity water north and south of the bay. A pattern of isohalines, broken at San Francisco Bay, is shown in charts for April through August. The pattern is simpler for the remainder of the year although the data for January, February, and March are not clear.

South of Monterey Bay water with salinity > 33.4‰ is always present in the mean. This salinity is greater than that found farther from the coast. The coastal high salinity is maintained by upwelling in the spring and summer and by the high salinity of the countercurrent (either directly by the advection or by vertical mixing with submerged countercurrent waters) in autumn and winter.

Upwelling regions have high-salinity water in spring and summer. Beginning in March and carrying through until July an isolated high-salinity region develops along the coast north and south of Point Conception and among the Channel Islands. In August through October the isolated high-salinity region is found only among the islands having successively smaller extent. The large temperature gradient (6° C. in 120 miles in June) occurs within this body of water. In part, the high salinities are formed by upwelling in the vicinity of Point Conception and the distribution is further influenced by the circuitous flow of the large eddy. The mass distribution associated with geostrophic balance requires that denser water, in this instance the higher salinity water, be found at shoaler depths to the left of the direction of flow (in the northern hemisphere). The spring increases in current flow amplifies this effect. The reestablishment of the large eddy in June centers the denser water in the island region and causes the mixed layer to be thin. In the Channel Island region, at depth, there is a greater percentage of water of southern origin than offshore (Sverdrup and Fleming, 1941). This water has a higher salinity at a given density than water of northern origin. All of these facts favor high salinities in the island region.

The seasonal variation of salinity off southern Baja California is markedly affected by advection. Starting in spring and developing into early summer the isohalines bend sharply towards the southeast. The lower salinities form a tongue-like distribution. The higher salinities along the coast must in part be maintained by upwelling. The northwestward projection of high salinity water near Punta Eugenia in September indicates an influx of more southerly water and corresponds to a cyclonic eddy sometimes found there in this season.

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NEW CHARTS COMPARED TO PREVIOUS CHARTS

The mean (monthly) temperature and salinity charts of CalCOFI Atlas No. 1 were constructed from station averages with a base period of 1950–59. Station averages based on fewer than five observations (for each month) were not used. Consequently, the distributions for some months have large gaps. The distributions of properties in the Atlas No. 1 charts and these newer charts are closely similar. The larger differences are in the salinity charts and in the areas of limited sampling. No attempt is made to provide representative differences because in some areas small differences may mean a large displacement of an isopleth whereas in other areas the opposite is true. The change in base period has an uneven effect depending upon sampling frequency and its change. The addition of the 33.5‰ isohaline (half of the standard interval) in the newer charts adds important definition.

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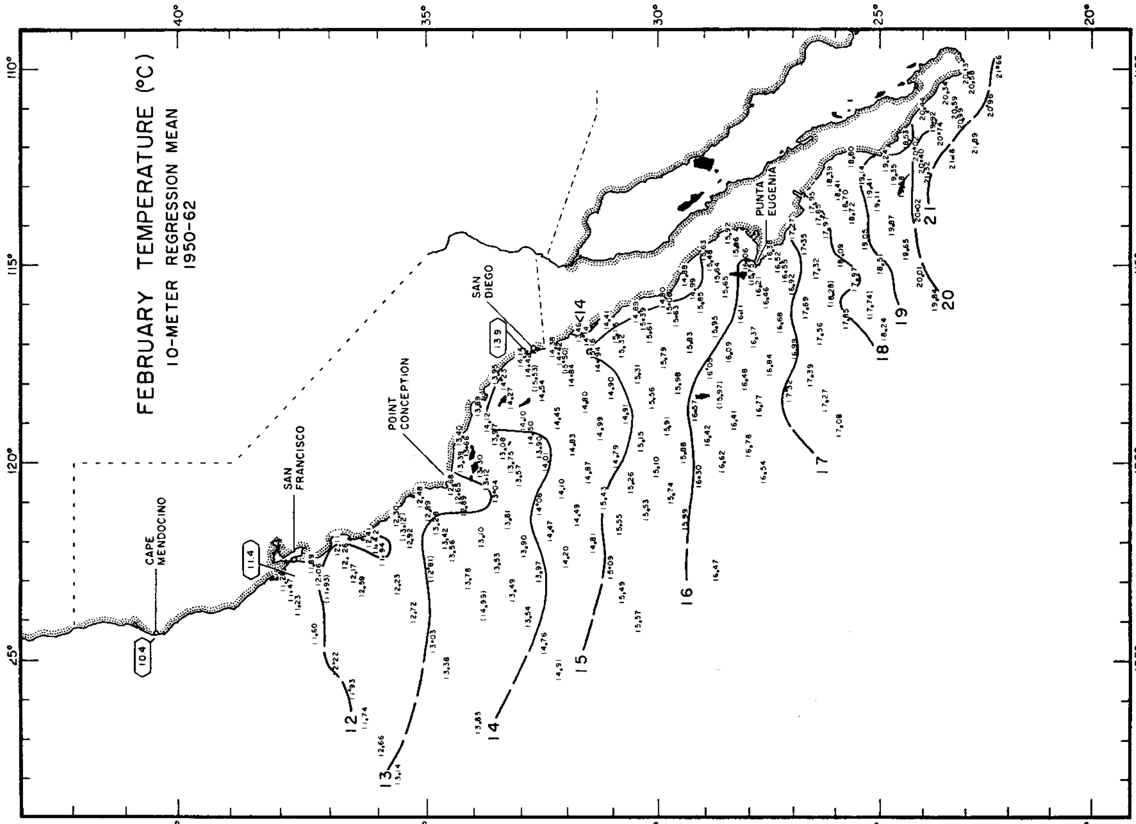
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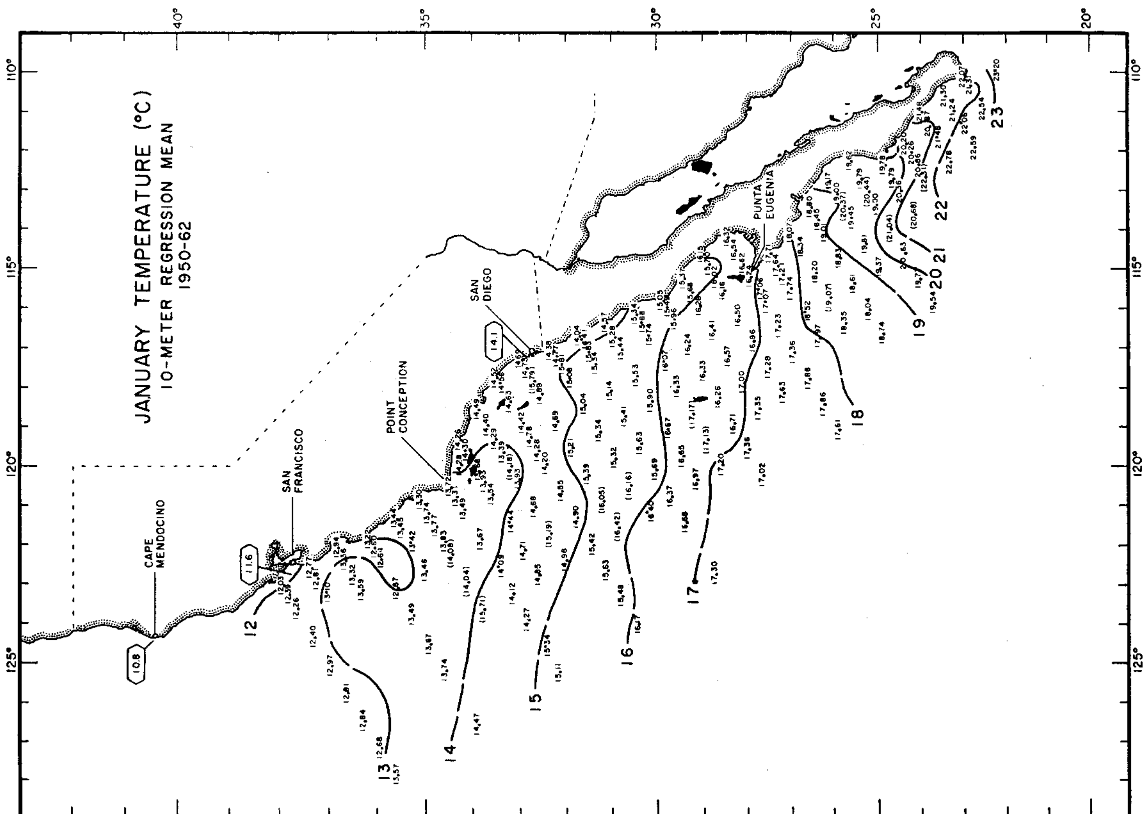
POINT CONCEPTION
SAN DIEGO
PUNTA EUGENIA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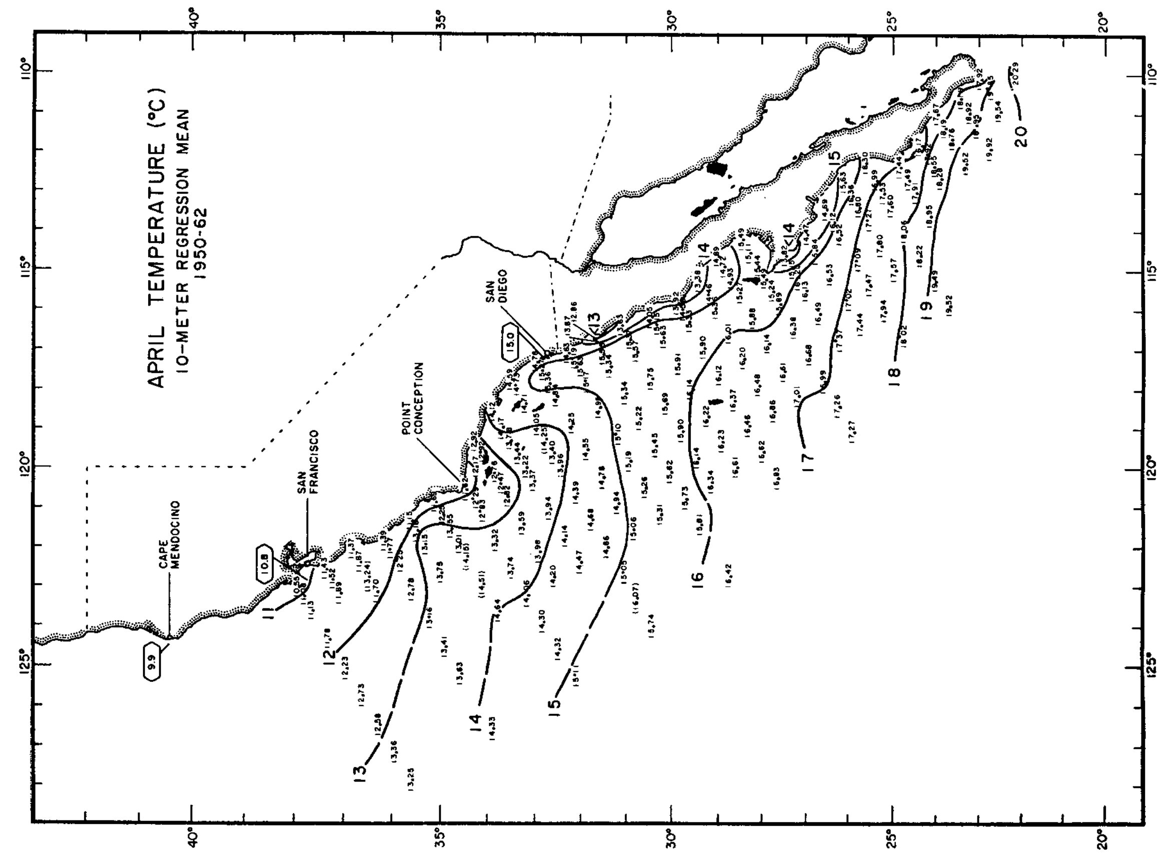
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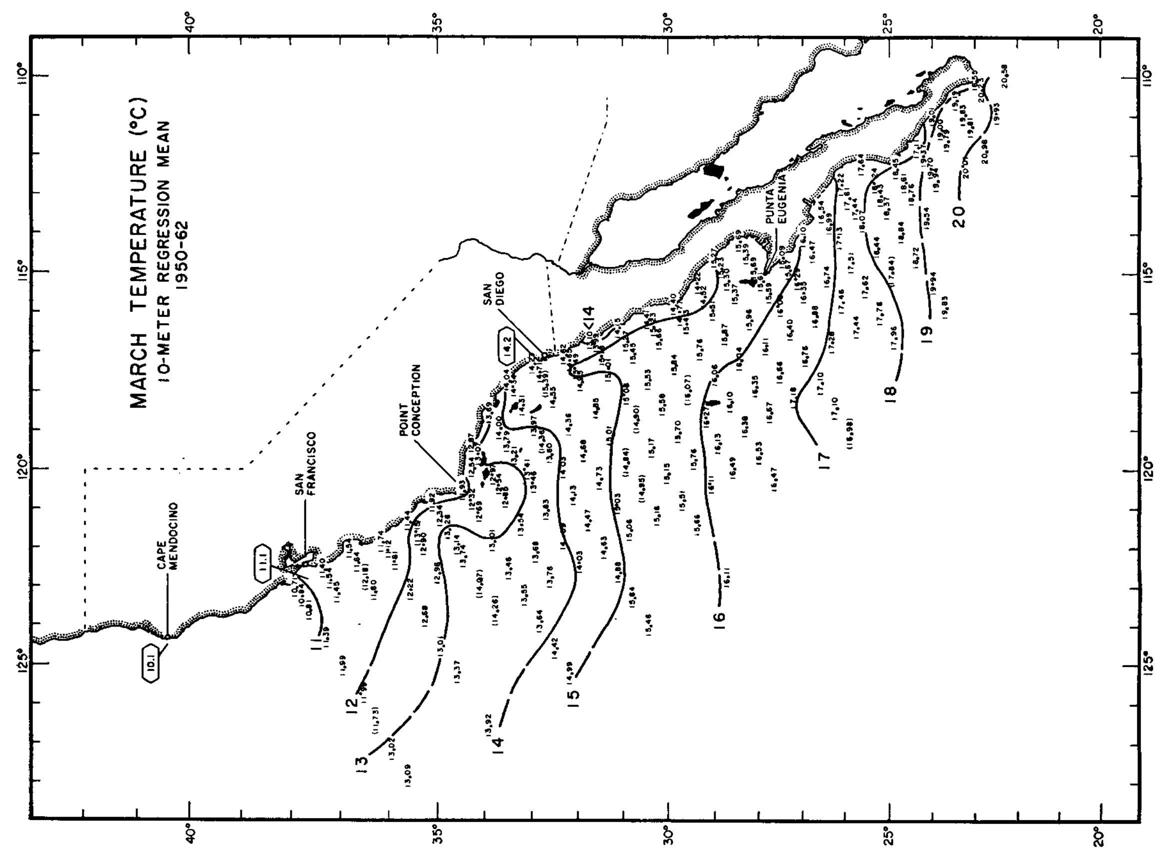
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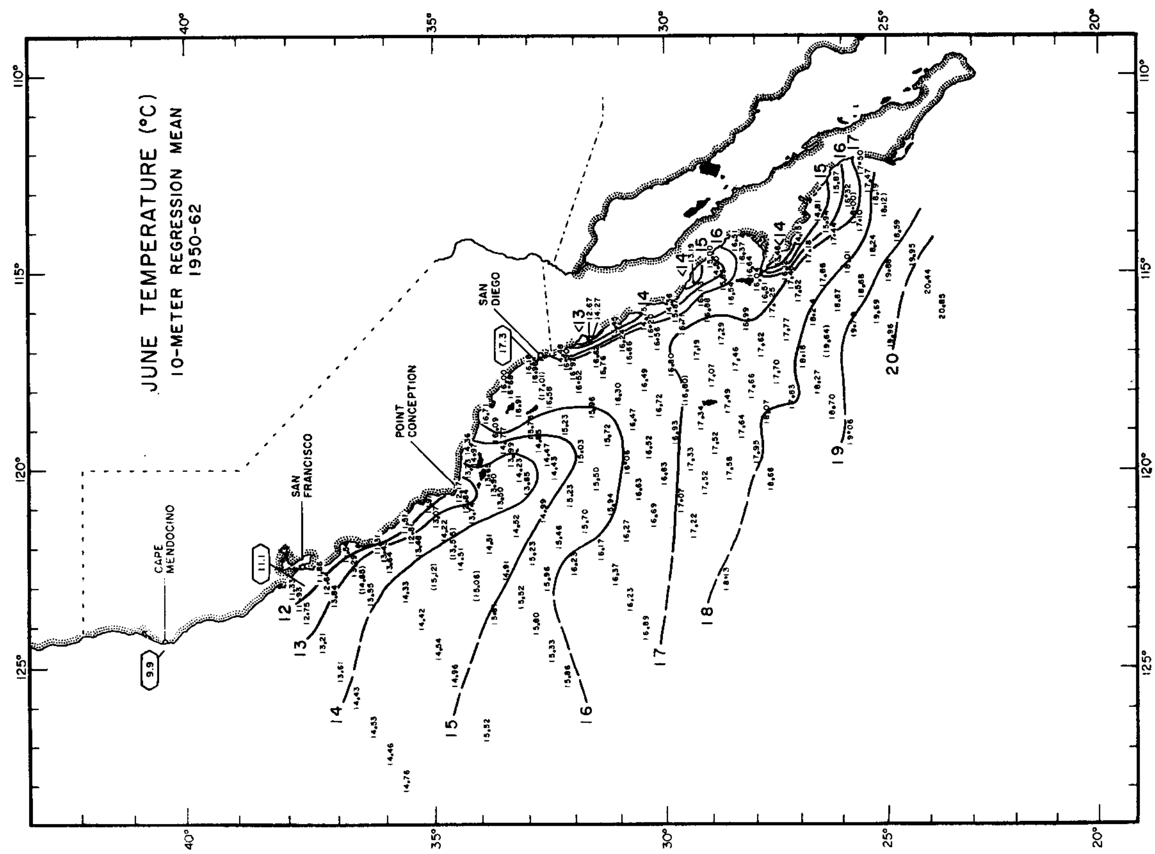
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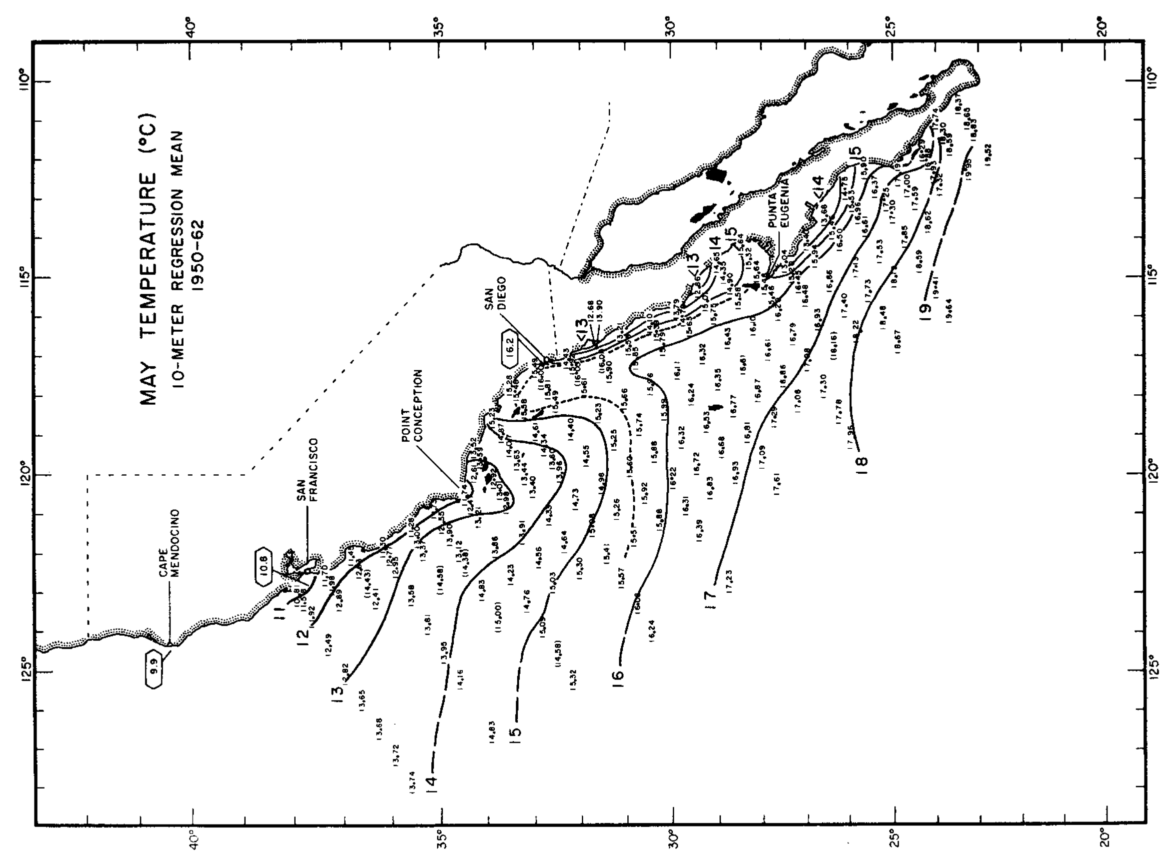
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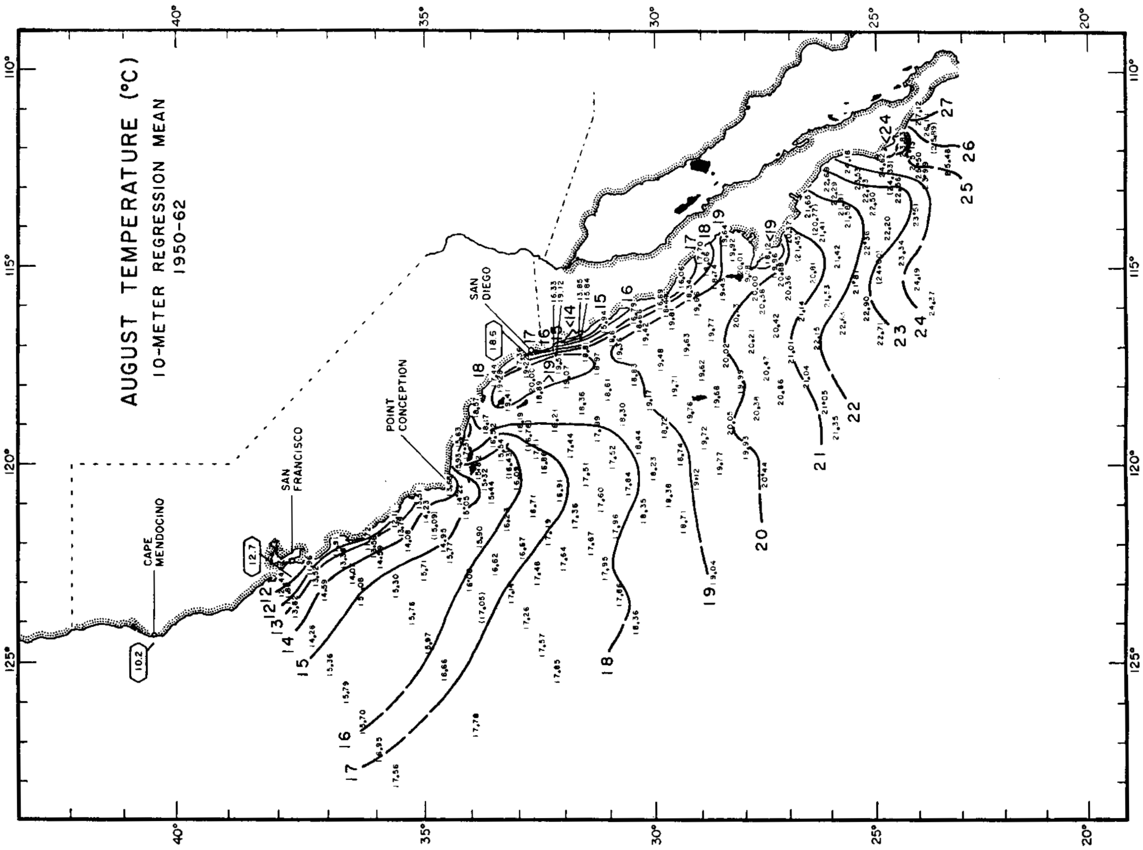
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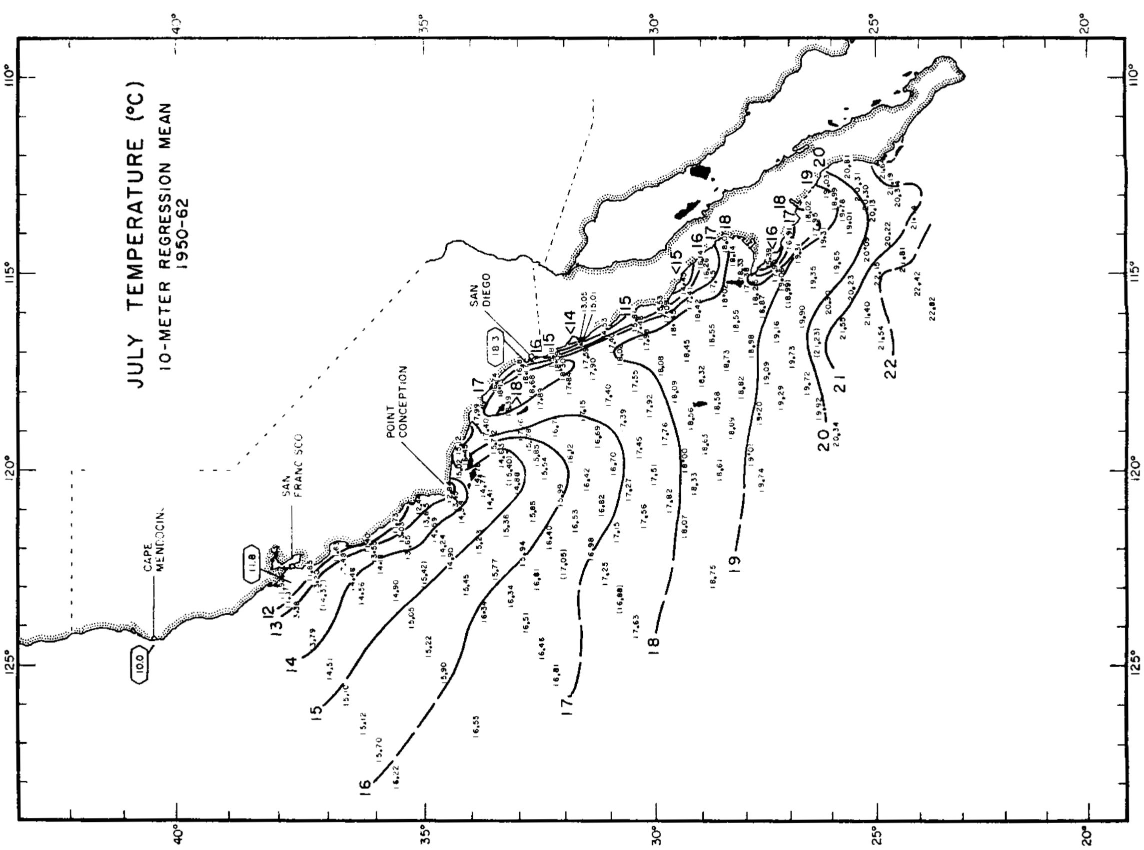
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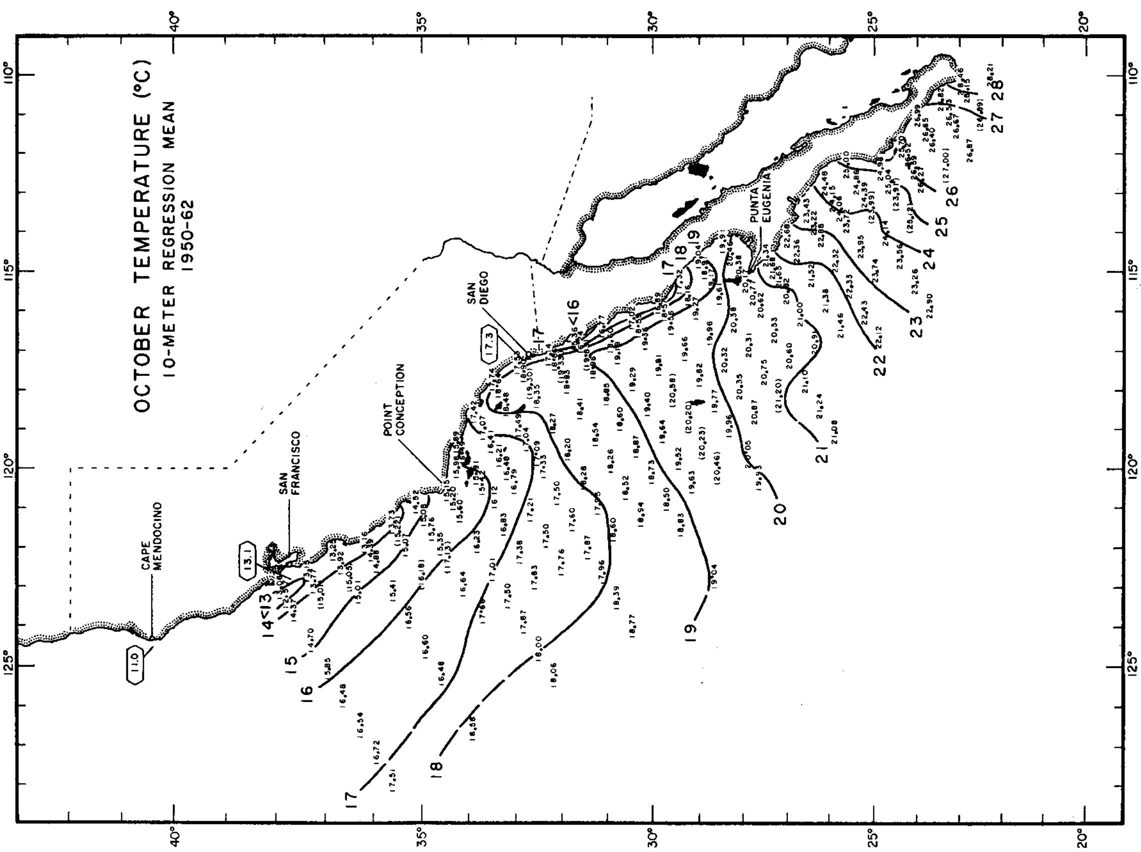
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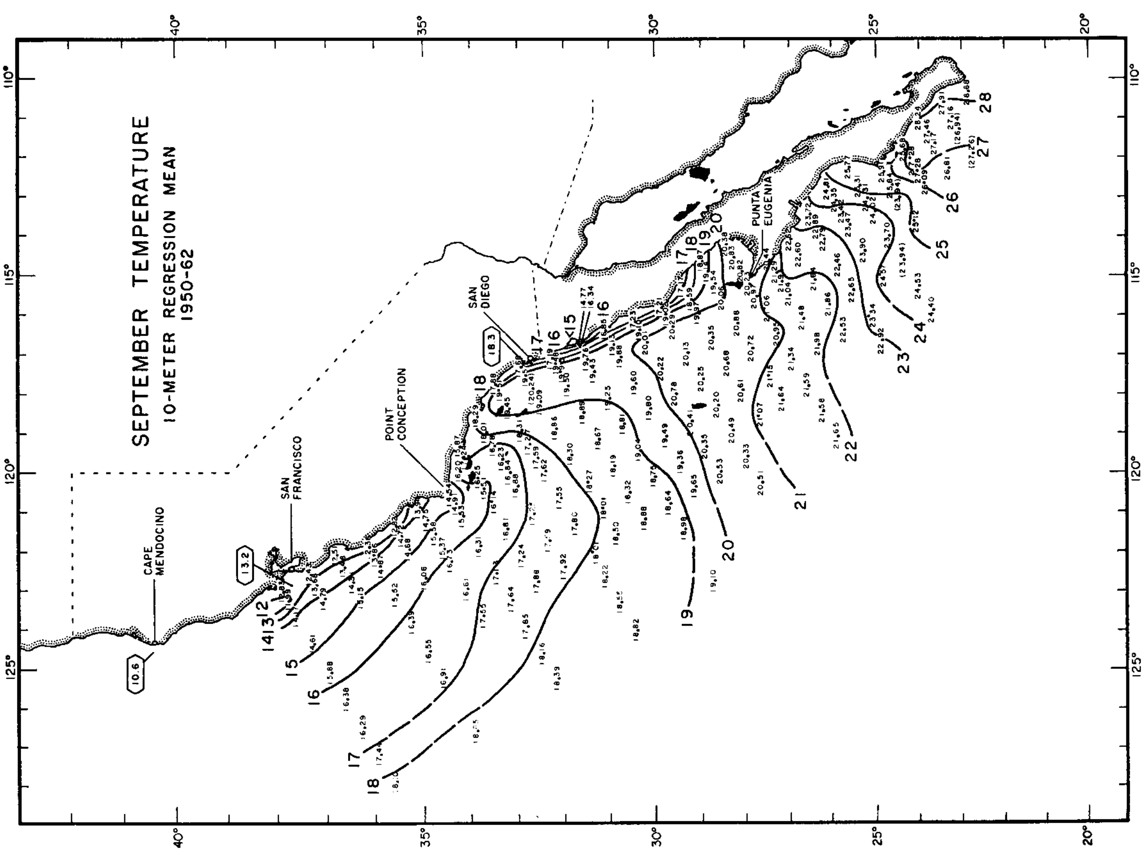
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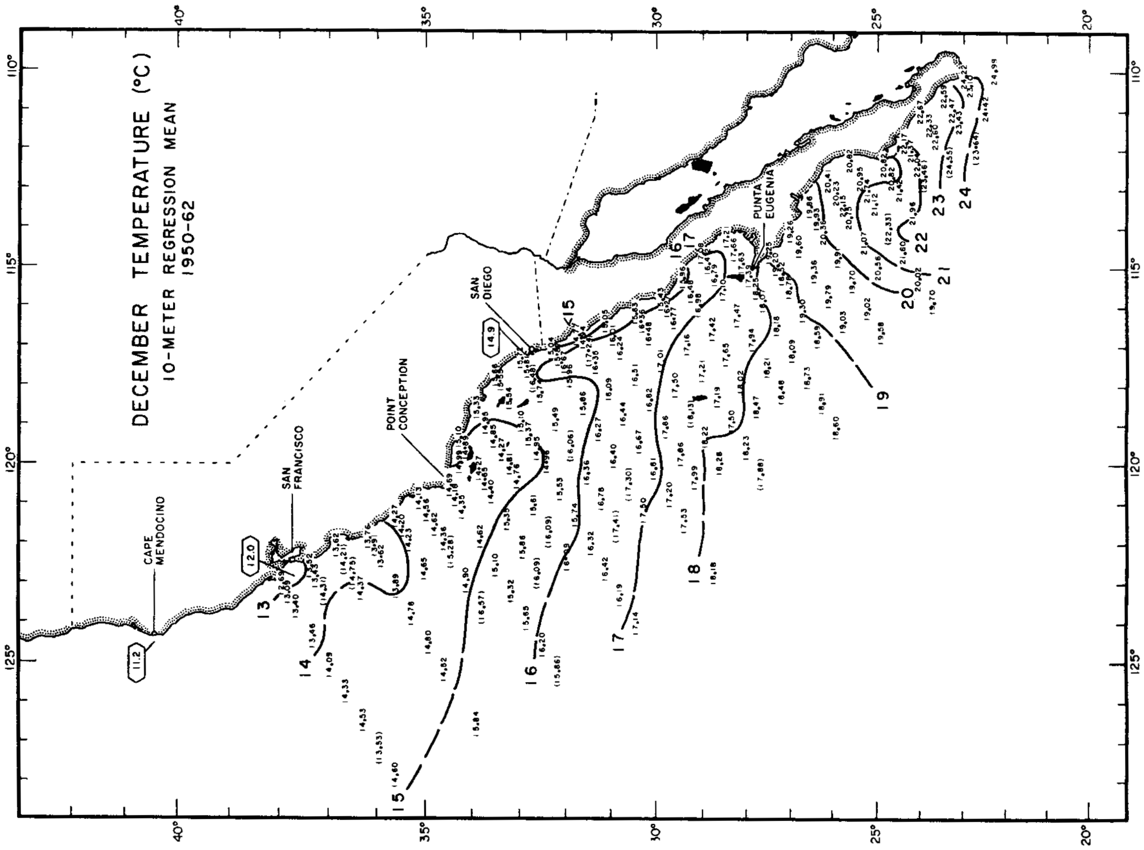
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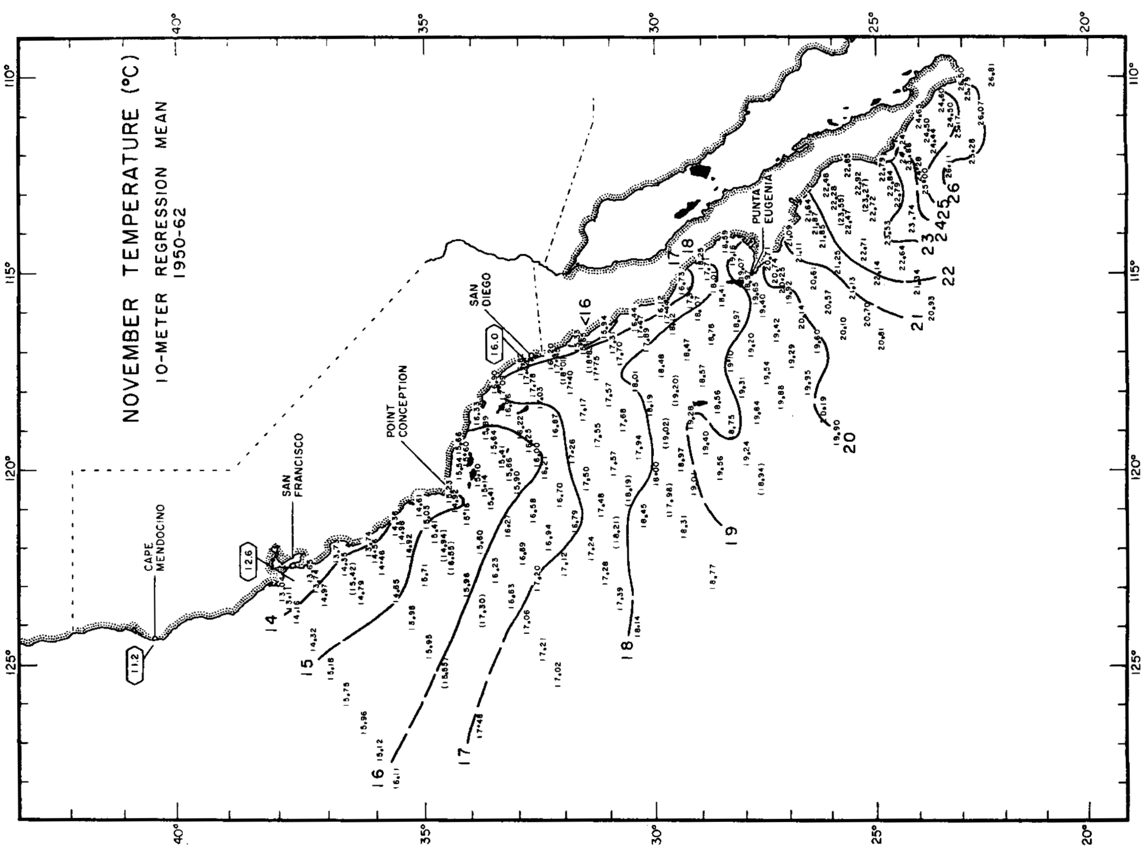
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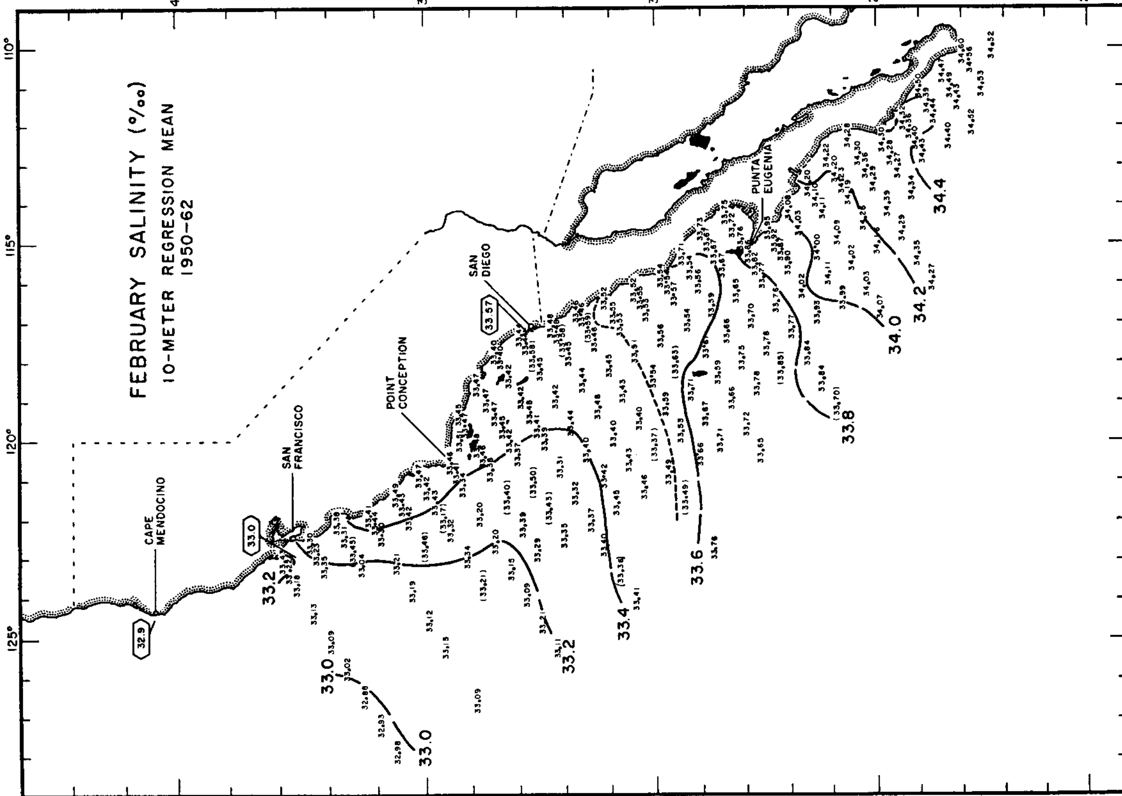
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1950-62
CAPE MENDOCINO
SAN FRANCISCO
POINT CONCEPTION
SAN DIEGO
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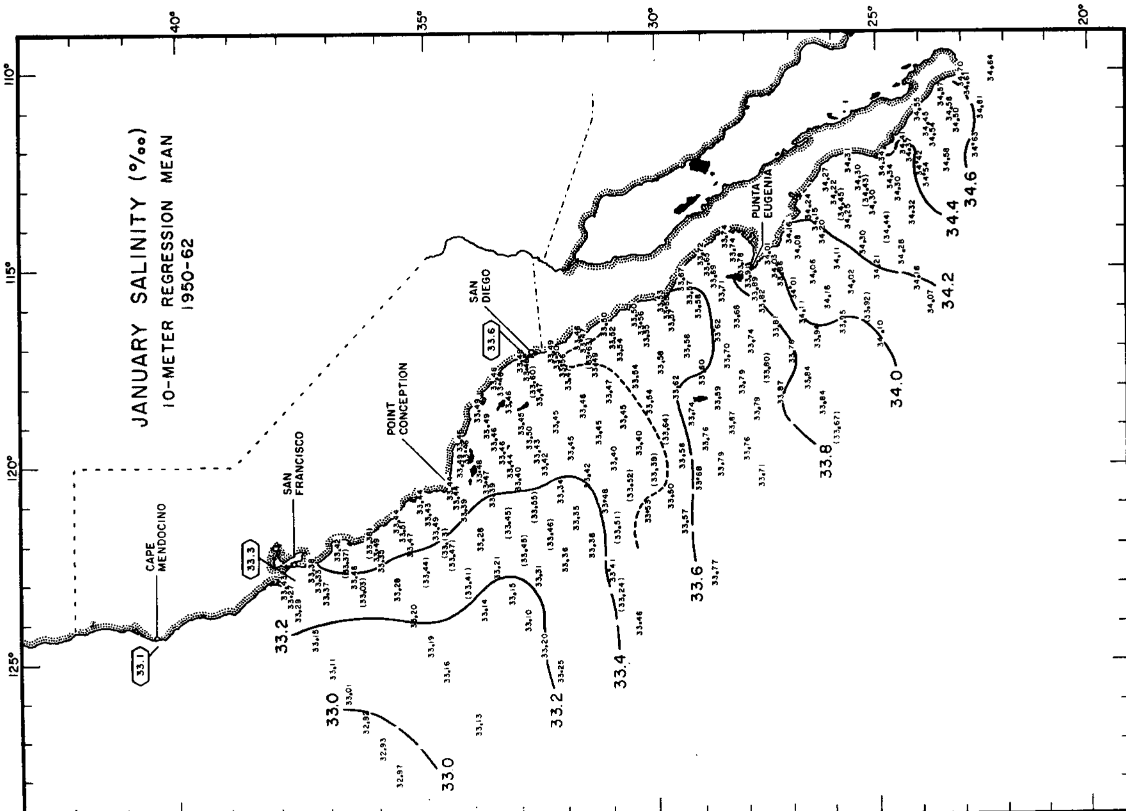
33.2
33.4
33.6
33.8
34.0
34.2
34.4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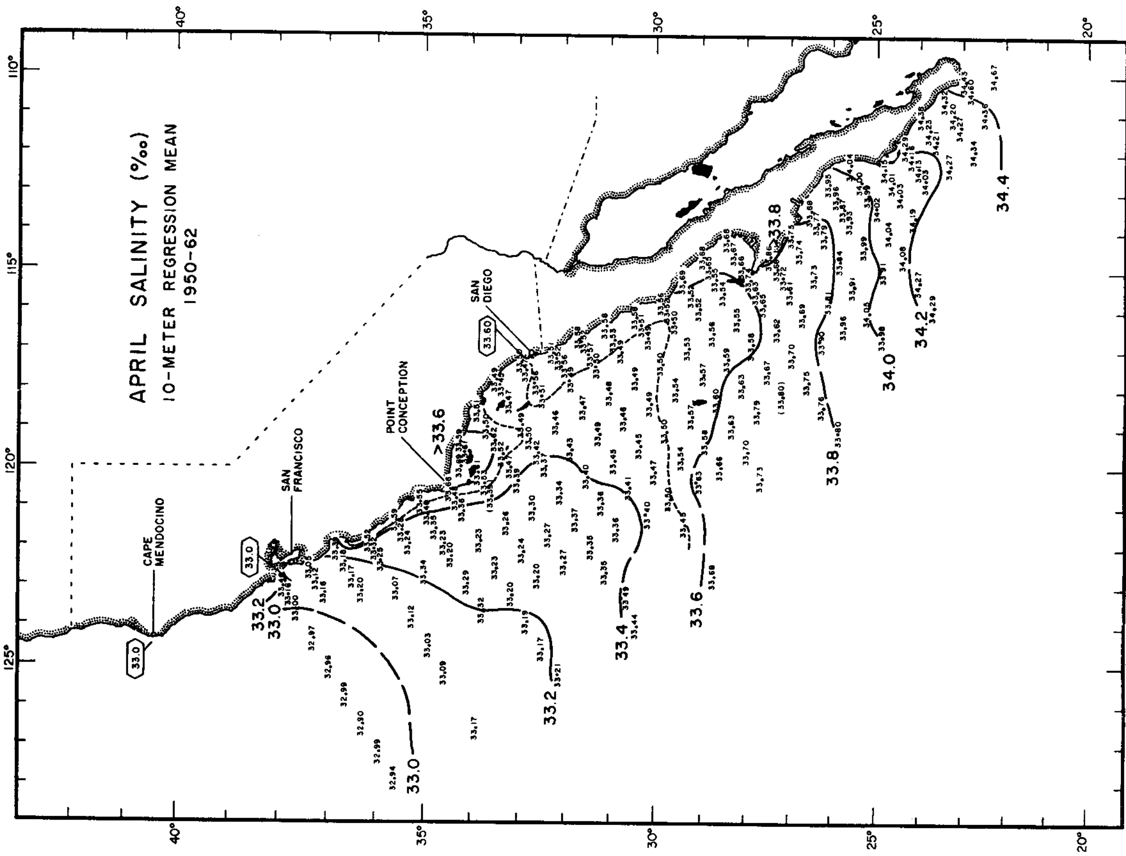
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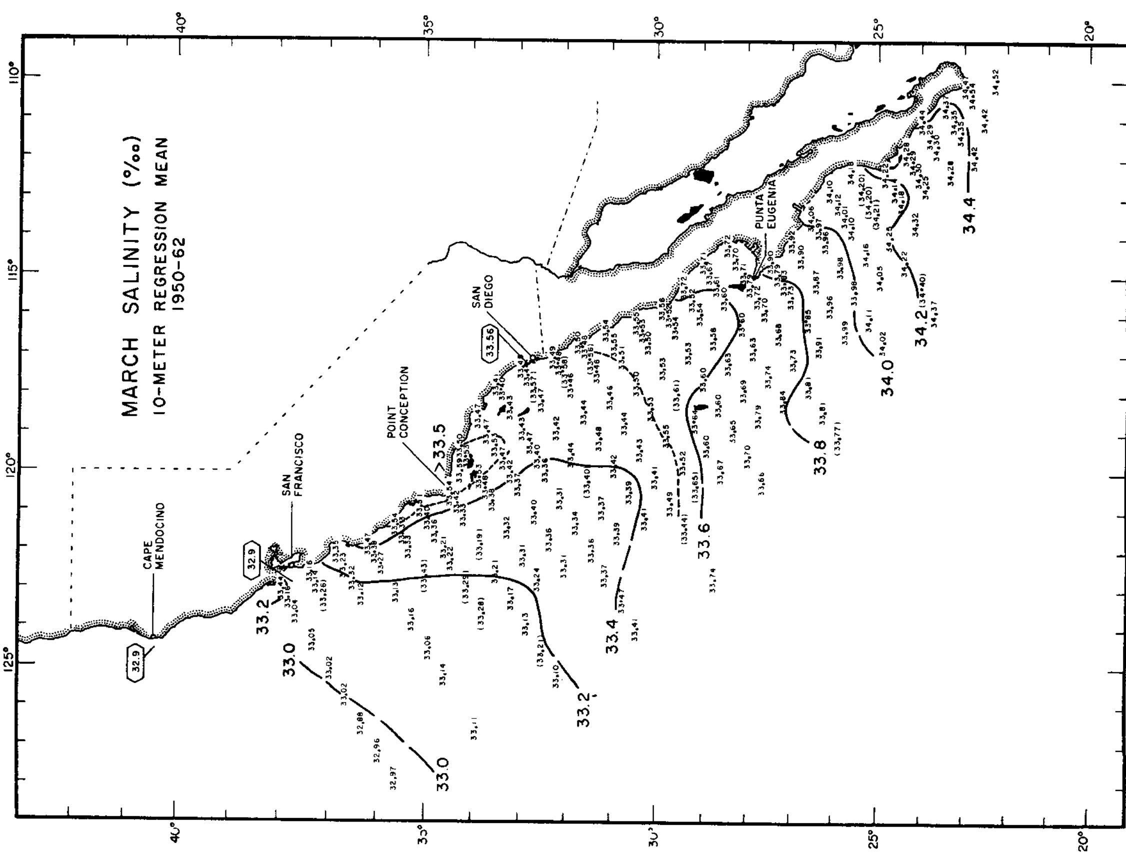
POINT CONCEPTION
SAN DIEGO


MARCH SALINITY (‰)
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1950-62
CAPE MENDOCINO
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POINT CONCEPTION
SAN DIEGO
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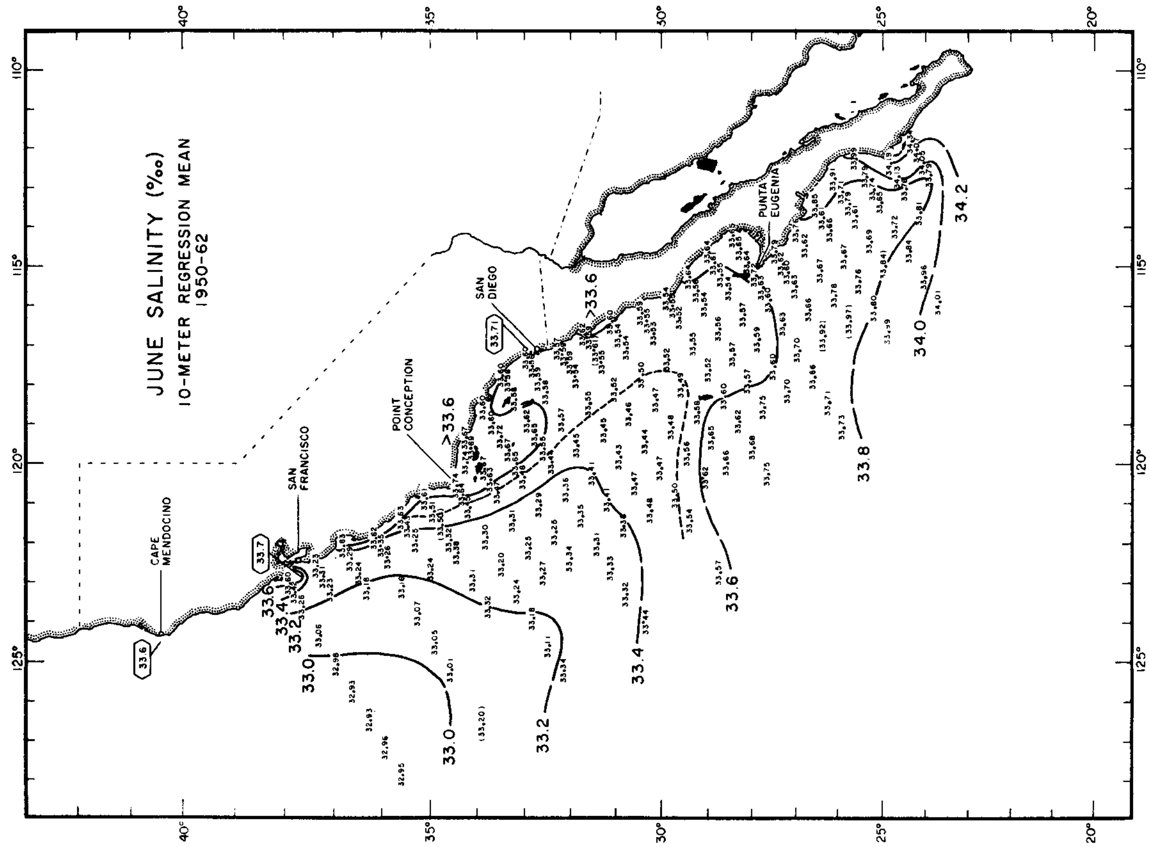
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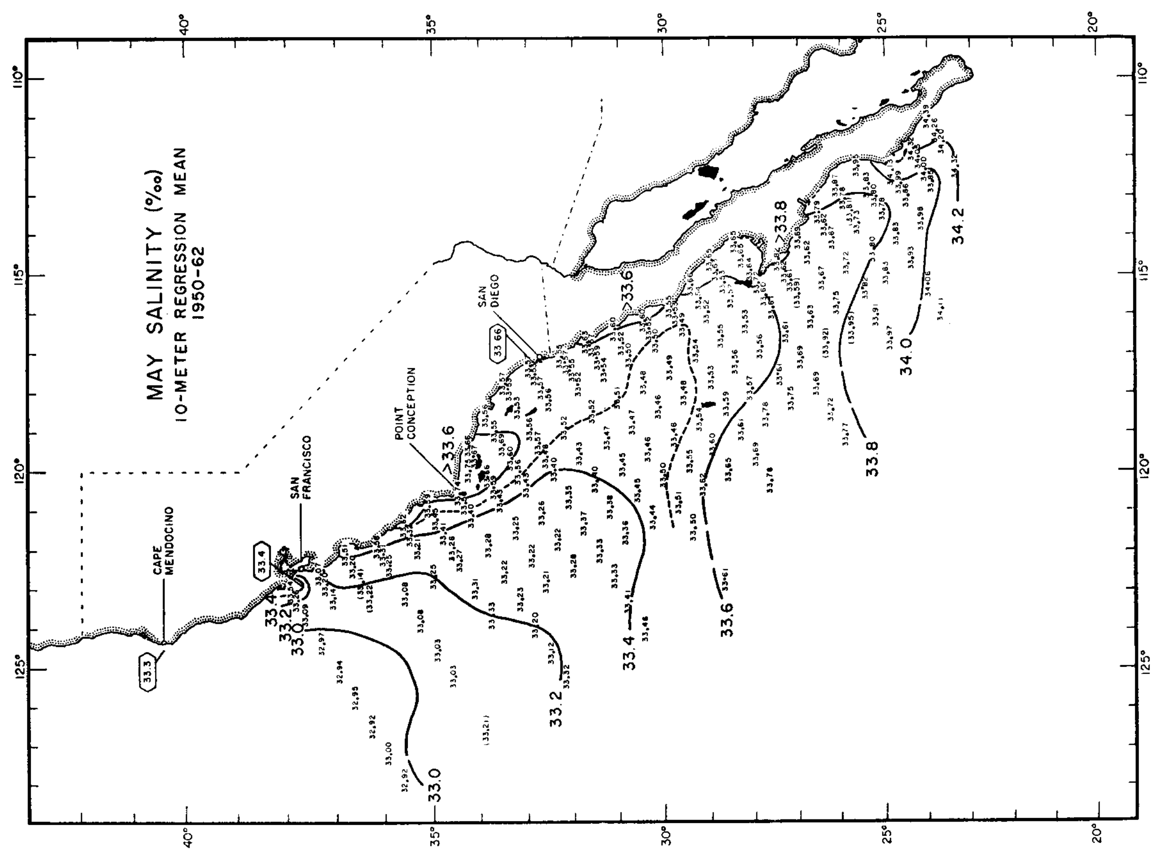
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POINT CONCEPTION
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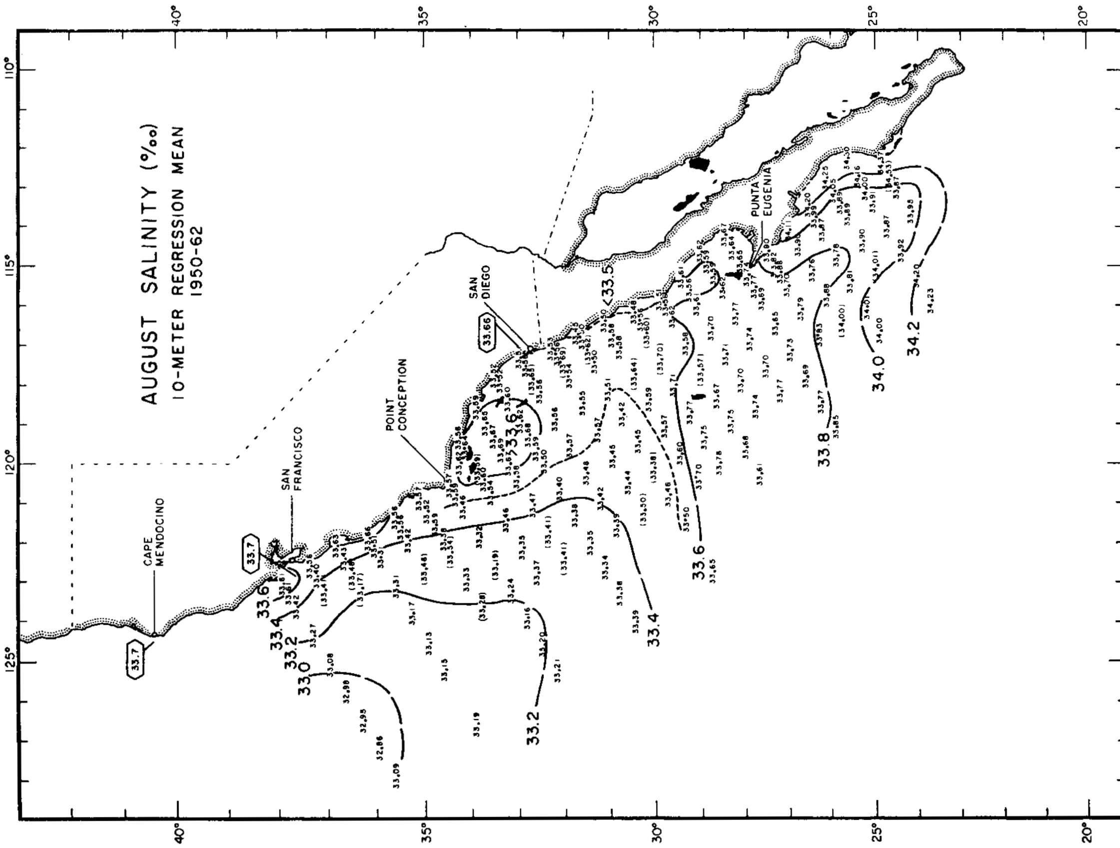
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1950-62
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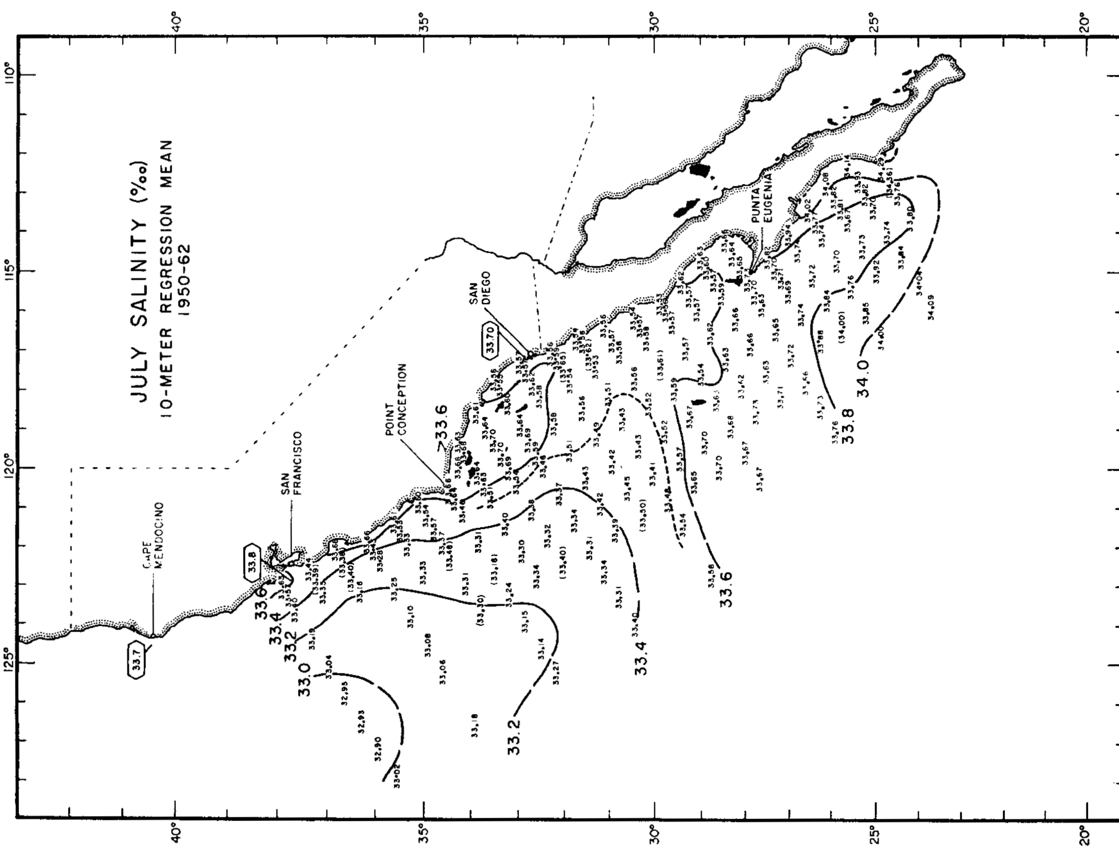
JULY SALINITY (‰)
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1950-62
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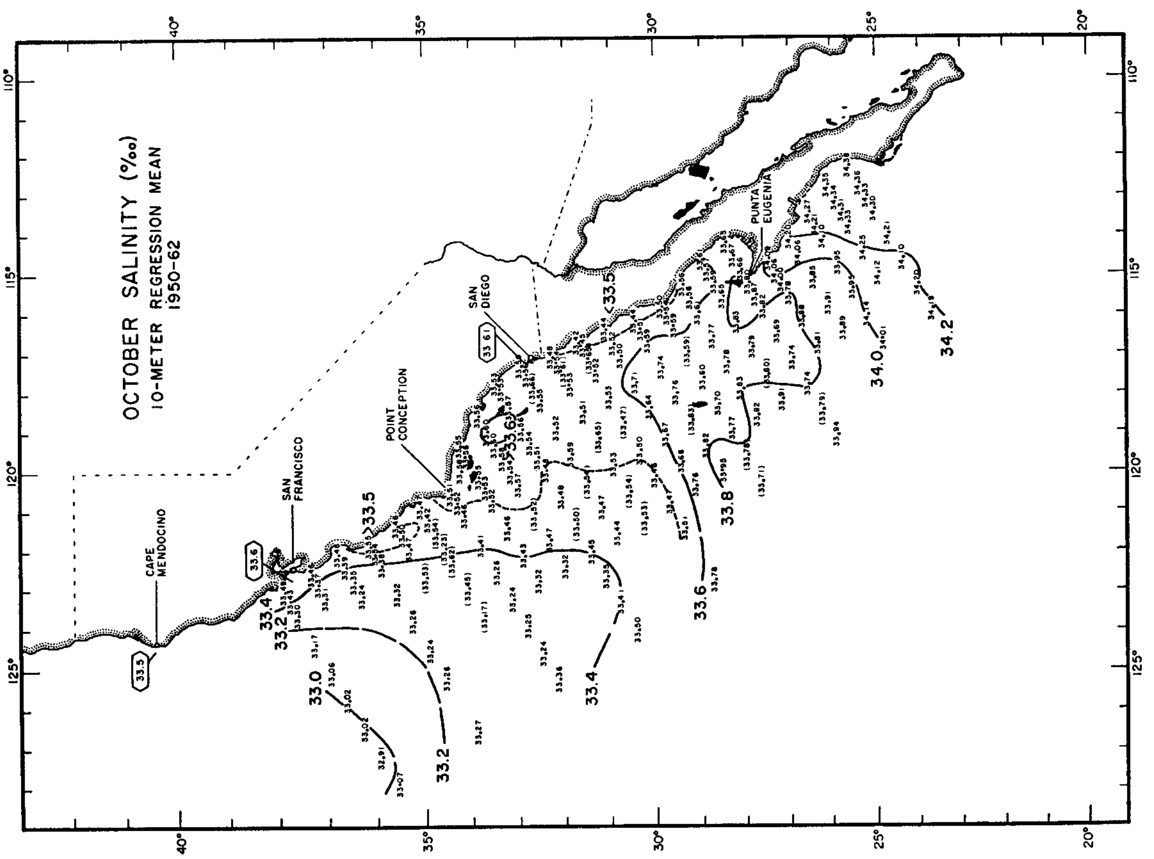
OCTOBER SALINITY (‰)
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1950-62
CAPE MENDOCINO
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POINT CONCEPTION
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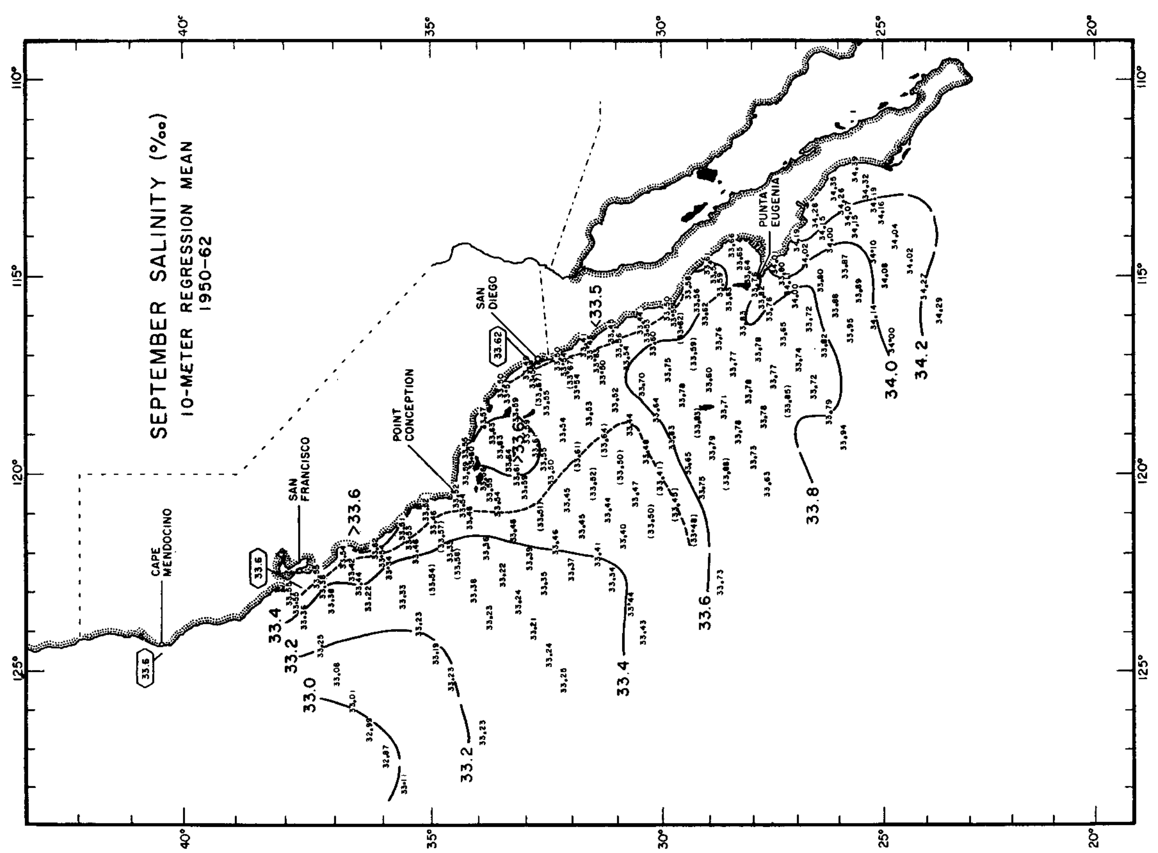
SEPTEMBER SALINITY (‰)
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1950-62
CAPE MENDOCINO
SAN FRANCISCO
POINT CONCEPTION
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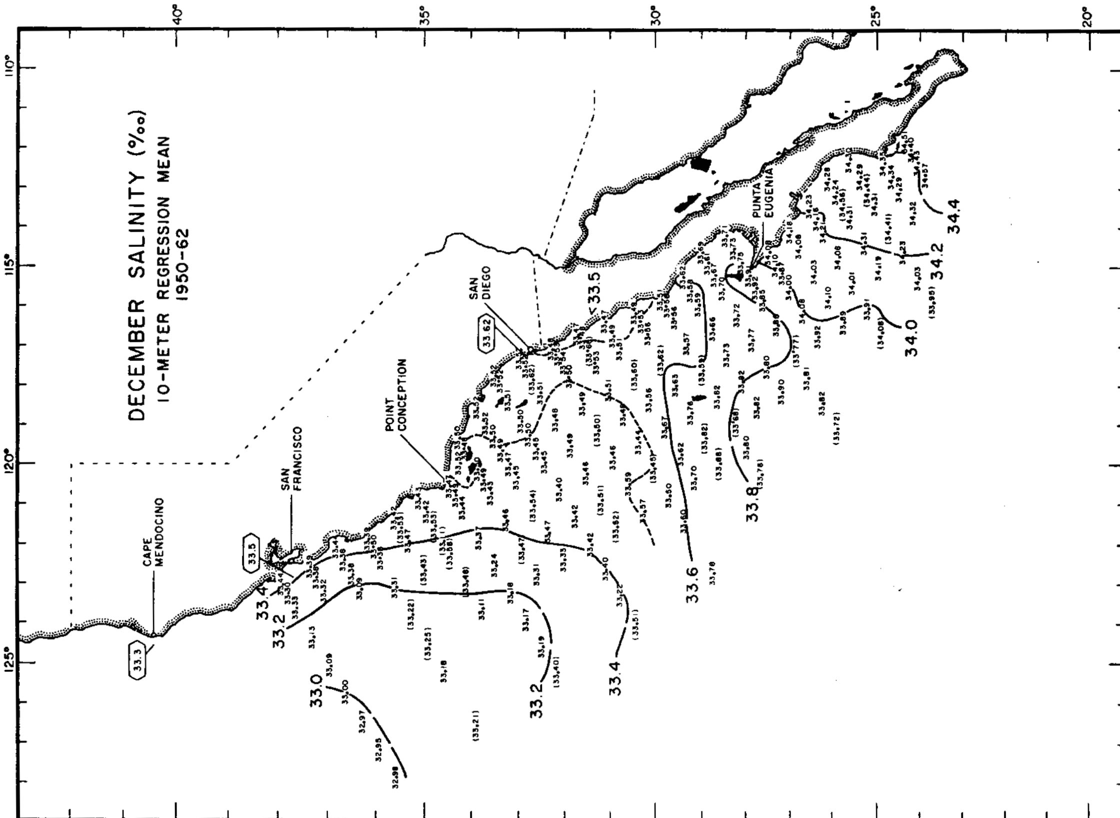

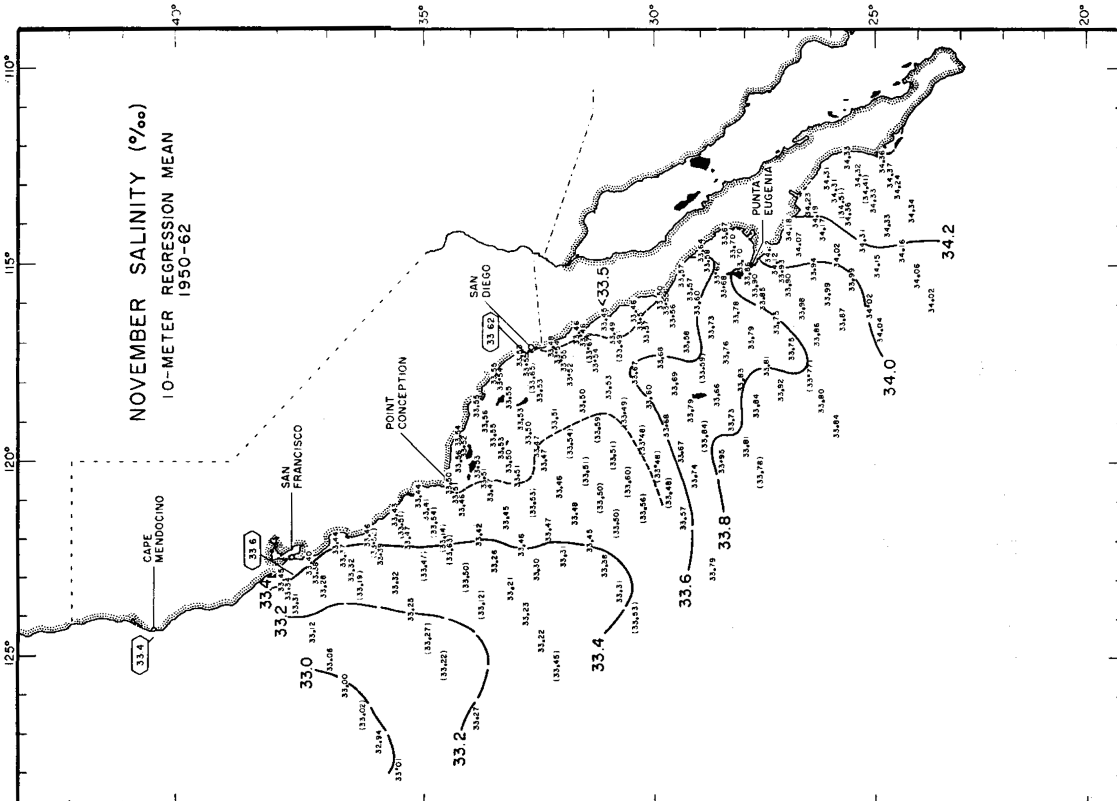

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