Spatial Characterization of Four Water Column Parameters on the Mainland Shelf of Southern California in July 1994

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ABSTRACT

A 261-site water quality survey of the southern California coastal shelf was conducted between July 12 and July 18, 1994. Surface temperatures ranged from 14.2 to 22.0° C and bottom temperatures ranged from 8.9 to 18.8° C. Surface salinity ranged from 33.0 to 34.1 practical salinity units (psu), while bottom salinity ranged from 33.4 to 34.2 psu. Surface dissolved oxygen ranged from 6.6 to 11.0 mg/L (90-135% saturation), while bottom oxygen ranged from 2.5 to 10.3 mg/L. Surface light transmittance ranged from 57.3 to 87.6% and bottom light transmittance ranged from 34.8 to 90.0%. Three dominant broad-scale spatial patterns were apparent. First, surface water patterns were strongly related to latitude; the northern portion of the study area was colder, less saline, and higher in dissolved oxygen than the southern portion. Second, water parameters measured near the bottom were dominated by a relationship to site depth, with deeper waters being colder, more saline, and less oxygenated than surface water. Third, the presence of a subsurface oxygen maximum layer was evident throughout most of the coastal shelf. Fluorometer measurements taken in a subset of the study area showed an associated subsurface chlorophyll maximum layer slightly below the oxygen maximum layer. A number of near-coastal features were observed, such as canyon upwelling and riverine input, that add background context to the highly focused publicly owned treatment work (POTW) sampling programs.

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INTRODUCTION

The Southern California Bight (SCB) is a topographically and oceanographically diverse coastal region. Among the factors contributing to this diversity are the numerous canyons, headlands, basins, islands, and regions of varying shelf width (<5-40 km) (Emery, 1960). Although the major equatorward-flowing California Current significantly affects the western coast of the United States, its direct influence is lessened within the SCB in that the majority of its transport occurs from 200 to 500 km offshore. Originating near the United States-Mexico international border as a branch of the California Current, the Southern California Countercurrent forms as an eddy that dominates surface flow over the continental slope area of the SCB as a poleward-flowing counter current (Hickey 1993, Tsuchiya 1980). Additionally, a poleward-flowing subsurface current (California Undercurrent) of southern origin dominates the nearshore continental slope area, typically between 100 and 300 m in water depth. The movements of near-surface currents over the mainland continental shelf appear to be predominantly equatorward (Hickey 1993). Driven by these current patterns, three distinct water masses mix within the SCB (Table 1). Sverdrup and Fleming (1941) observed that, within the SCB, northern water dominates the surface; whereas southern water dominates at greater depths. The influence of water of southern origins was stronger near the coast. Pacific equatorial water tends to move as a narrow jet, carrying water north near the coast within the California Undercurrent (Wooster and Jones 1970, Tsuchiya 1980).

Most studies of SCB physical oceanography have focused attention upon water movement or water column properties of the major currents over basins and other outer SCB regions (Hickey 1993). The CalCOFI surveys (Lynn and Simpson 1987) were the longest in duration of these studies, having collected water property data on a

TABLE 1. Relative water column properties from each of the water masses comprising the California Current system within the Southern California Bight.

Source	Water Column Properties: Temperature	Salinity	Dissolved Oxygen	Nutrients
Pacific Subarctic (Reid *et al.* 1958)	Low	Low	High	High
No. Pacific Central (Reid *et al.* 1958)	Warm	High	Low	Low
Pacific Equatorial (Pickard 1964)	High	High	Low	High

seasonal basis at fixed stations from northern California to lower Baja California, Mexico, since 1950. For the past 10 years at a minimum, quarterly surveys have been conducted at a smaller subset of stations (approximately 100, along 6 transect lines) from Point Conception to the United States-Mexico international border. While these surveys provide valuable time-series data, the stations are widely spaced and are located primarily offshore; only six CalCOFI stations are located along the coastal shelf (less than 200 m deep).

The most comprehensive surveys of coastal shelf waters are the ongoing programs conducted by the four largest major POTWs. These organizations sample waters near their respective wastewater outfalls monthly (CLAEMD 1995, CSDLAC 1995, CSDMWD 1995, OCSD 1996) or weekly (Dalkey and Shisko 1996). While spatially intensive, and yielding valuable time-series data within the areas they sample, these monitoring programs are limited to areas in proximity to their respective outfalls, which cumulatively account for less than 10% of the total area on the coastal shelf (Cross and Weisberg 1996). What is often lacking in these programs is adequate characterization of the water surrounding, and impacting, these sampling areas. Characterizing the surrounding waters can aid in the interpretation of data gathered from within outfall sampling areas. For example, in a 1993 study off the Orange County coast (OCSD 1994), efforts to map the extent of the outfall plume were confounded by influences emanating from Los Angeles-Long Beach Harbor.

Here we present the results of a comprehensive conductivity-temperature-depth (CTD) survey of the SCB coastal shelf (<220m). The intent of this study is to describe the broad physical spatial patterns in the near-coastal SCB as well as localized patterns, both naturally occurring and those of anthropogenic origins. This study provides a "snapshot" of shelf waters as well as a baseline for an ongoing time-series survey similar to those the CalCOFI surveys have provided for the outer SCB waters.

METHODS

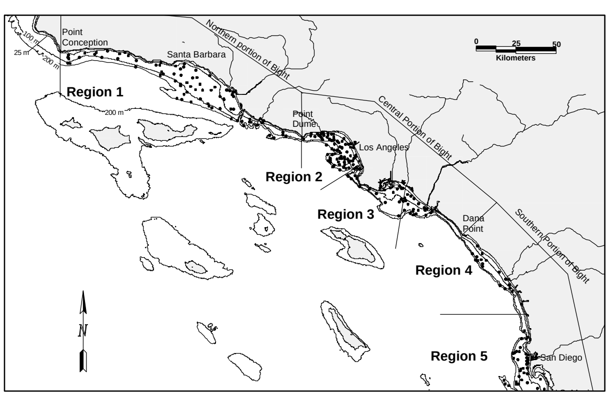
Study Design

The study area extended from Point Conception, California, to the United States-Mexico international border (Figure 1). We selected 264 sites using a stratified random sampling design, with depth and proximity to input sources (rivers and wastewater outfalls) as the primary strata. Details of site selection are provided in Bergen (1996) and Stevens (1997). Of the original 264 sites, 261 were sampled.

Field Methods

Sampling was conducted from July 12 to July 18, 1994, using five vessels. Four vessels conducted sampling activities between July 12 and 14; the fifth vessel experienced equipment problems and sampled between July 15 and 18. In all cases, sampling was limited to daylight hours. Crews sampled assigned areas in a semi-haphazard fashion (no progressive sampling) to minimize potentially confounding problems related to the movement of an oceanographic event, time of day, or tidal stage.

FIGURE 1. CTD stations (261) sampled on the mainland shelf of southern California ranging in depth from 8-218 m. Each region represents an area covered by one of five vessels used in the survey.



Sea-Bird Electronics (Model SBE 9 or SBE 25) CTD profilers were used to obtain a continuous record of water column parameters (temperature, salinity, dissolved oxygen, and light transmittance) from the surface to the bottom. Salinity was calculated based upon conductivity, temperature, and pressure from the 1978 practical salinity scale (Fofonoff and Millard 1983) and reported as psu.

Two quality assurance methods were utilized to maximize precision and accuracy among CTDs. First, all CTDs used in the study were placed in a common temperature-controlled, air-saturated seawater tank prior to the survey. During this exercise, data were compared among CTDs to assess precision. Comparing data against standards or reference instruments provided measures of accuracy. Second, each instrument was individually pre-calibrated 24 h prior to the survey start and post-calibrated within 24 h of the survey completion. This dual calibration method provided a measure for assessing any sensor drift that occurred during the survey.

Data Analysis

Analysis was based upon downcast data, which were screened for obvious discontinuities that could be attributed to equipment malfunction; 0.2% of the data, 87% of which were salinity values, were removed. Data analysis was conducted primarily using surface and bottom layers. Surface values were defined as the mean of the top 3 m of the water column; bottom values were defined as the mean of the last 3 m of a cast. Mean values for the SCB were calculated by weighting samples in accordance with their inclusion probabilities from the stratified design.

Each response measure was displayed as a three-dimensional surface defined by latitude and depth. These plots were based upon a distance–weighted, least-squares smoothing method (Wilkinson 1996). Isopleths were linearly interpolated to depth from averaged station casts representing sites throughout the survey from specific station depths or SCB area (north - Point Conception to Point Dume; central - Point Dume to Dana Point; and south - Dana Point to the United States-Mexico international border).

Regression analyses were used to assess the relative influence of depth and latitude on water column parameters. Regressions were calculated as second-order polynomials to allow for the possibility of non-linear relationships. Regressions were also used to identify sites with unusual values that were defined as those falling outside of the 95% confidence interval of the regression relationships.

RESULTS

Temperature

Surface temperatures throughout the survey area ranged from 14.2 to 22.0° C with a mean temperature of 18.1° C (Table 2). Temperature trended (Figure 2a) higher from north (Point Conception) to south (United States-Mexico international border). Site depth had little apparent influence on surface temperature (Table 3). Three groups of cold water outliers were apparent (Figure 3). Five sites in the south (below 32.9° N) exhibited surface temperatures as much as 2° C colder than surrounding water (Figure 4a). Sites nearest the Los Angeles-Long Beach Harbor breakwater exhibited the coldest water in the central portion of the study area (Figure 4b). In the north (>34.0° N), near an offshore canyon area, areas of cold water pockets were also found (Figure 4c).

Temperature decreased with depth in the water column (Figure 5). Isotherms exhibited the greatest compression between 8 and 20 m (Figure 6a). Isotherms sloped slightly upward and began narrowing as they approached the shore. Maximum isotherm compression occurred in the southern region of the SCB in near surface waters in an area between Dana Point and the Santa Margarita River (Figure 6b).

Bottom temperatures ranged from 8.9 to 18.8° C with a mean temperature of 11.0° C (Table 2). Bottom temperature was strongly related to station depth (Figure 2b). Shallow stations exhibited the highest variability, whereas areas more than 40 m in depth had relatively homogenous temperatures, ranging between 8.9 and 11° C. The transition from heterogeneous to homogenous bottom temperatures corresponded to the thermocline depth, which marks the break between upper mixed waters and deep waters (Figure 5).

Salinity

Surface salinity was relatively homogeneous throughout the SCB (Figure 7a). The highest values where found in the south, where a subsurface salinity minimum layer was present. Surface salinity ranged from 33.0 to 34.1 psu, with a mean salinity of 33.5 psu (Table 2). All but a few sites ranged between 33.3 and 33.7 psu. Highly localized anomalies were found at three sites (Figure 8). The area with the highest salinity (0.38 psu higher than surrounding sites) was identified at the head of La Jolla Canyon (Figure 9a). The two sites with the lowest salinity (0.19 psu or lower) were sampled closest to Los Angeles and the San Gabriel River discharge (Figure 9b).

TABLE 2. **Summary statistics for CTD parameters measured during July 1994.**

Category	No. of Stations	Range Min.	Range Max.	Stratified Values Median	Stratified Values Mean	Stratified Values SD	Stratified Values 95% CL
Temperature (°C)							
Surface	261	14.2	22.0	17.8	18.1	1.9	0.3
Bottom	261	8.9	18.8	10.3	11.0	1.8	0.3
Salinity (psu)							
Surface	261	33.0	34.1	33.4	33.5	<0.1	<0.1
Bottom	261	33.4	34.2	33.6	33.7	0.2	<0.1
Dissolve oxygen (mg/L)							
Surface	261	6.6	11.0	9.0	8.9	0.9	0.1
Bottom	261	2.5	10.3	5.5	5.9	1.9	0.3
Light transmittance (%)							
Surface	261	57.3	87.6	82.0	81.1	4.0	0.5
Bottom	261	34.8	90.0	82.4	79.9	8.1	1.2
Depth (m)							
Bottom	261	8.0	218.0	54.0*	74.0	55.0	8.0

Footnote:
Surface = Top 1-3 m; Bottom = Lower 3 m of cast;
Median = 50% of the area in the Southern California Bight; SD = Standard deviation;
CL = Confidence limit; Min. = Minimum; Max. = Maximum; psu = Practical salinity units;
D.O. = Dissolved oxygen; Transmission = Light transmission.
* = Median depth is un-stratified and represents the true statistical 50% value.

Salinity increased with depth in the water column (Figure 5). The area of the water column between the surface and 40 m was relatively isohaline and represented the thickest isopleth (Figure 10a). The greatest cross-shelf isopleth compression occurred between approximately 40 and 70 m. The north-to-south gradient (Figure 10b) revealed the lower salinity pockets from the rivers mentioned earlier and a subsurface salinity minimum layer present in the south.

Bottom salinity ranged from 33.4 to 34.2 psu with a mean of 33.7 psu (Table 2). Salinity exhibited a linear relationship with increasing depth (Table 3 and Figure 7b). The highest rate of change occurred at those sites with depths between 50 and 70m. Bottom water at sites shallower than 50 m were nearly isohaline (Figure 11).

Oxygen

Surface dissolved oxygen ranged from 6.6 to 11.0 mg/L with a mean of 8.9 mg/L (Table 2). Highest oxygen concentrations were generally associated with the colder northern waters, although an area of high oxygen concentration was also found in the southern portion of the study area (Figure 12a). Waters in the south-central portion of the study area, between 33.3 and 33.7° N, were lower in dissolved oxygen than colder northern waters; yet most were still above 100% saturation (Figure 13). Two groups of sites were supersaturated up to 135%. These sites were in similar areas (Figure 4a and 4c), with low temperatures relative to surrounding waters.

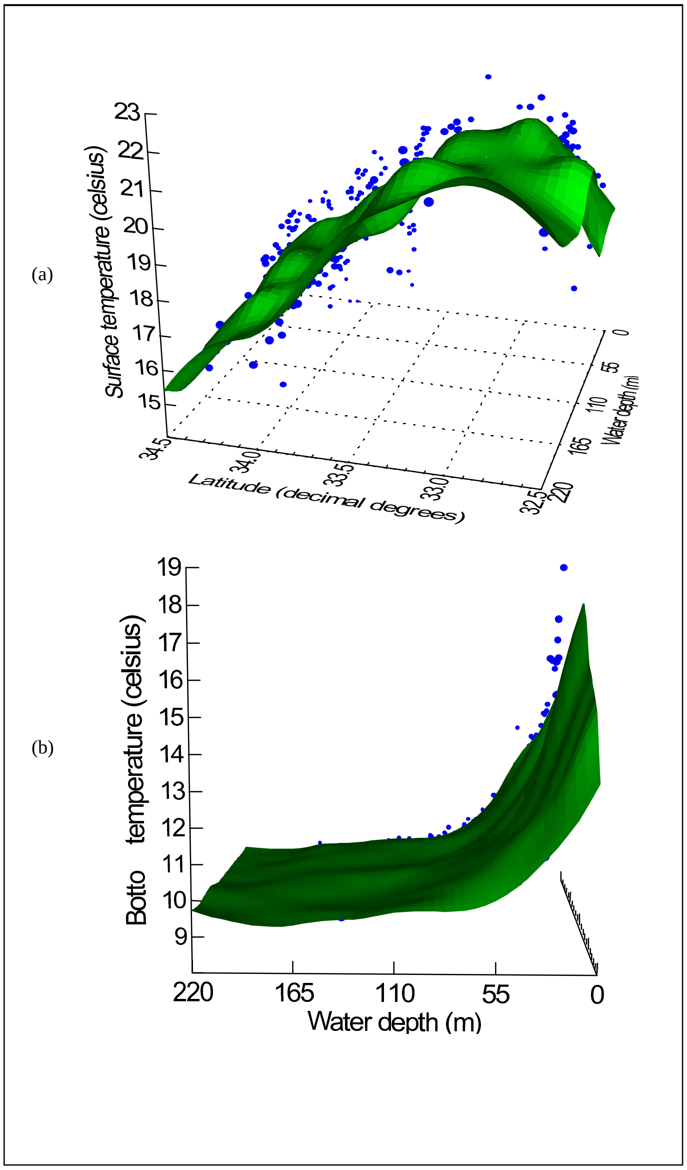
Throughout most of the SCB, a subsurface oxygen maximum layer peaked between 11 and 17 m in depth (Figure 5). This layer extended offshore to sites with depths greater than 200 m (Figure 14a), then narrowed as it approached shore. This layer also formed in the central and southern portion of the SCB (Figure 14b).

Bottom oxygen ranged from 2.5 to 10.3 mg/L with a mean of 5.9 mg/L (Table 2). No apparent latitudinal trend was observed in the data (Table 3). Concentration decreased with depth, with the highest bottom values found at sites of less than 25 m depth (Figure 12b).

Light Transmittance

Surface light transmittance (T) values ranged from 57.3 to 87.6% with a mean of 80.1% (Table 2). The clearest part of the water column was found between 45 and 82 m (Figure 5). No apparent geographical trend was observed in the data (Table 3). Surface light transmittance increased with distance from shore. Most sites (97%) ranged from 70 to 88% T. The lowest transmittance values (below 60% T) were found at six sites, three off the Santa Barbara coast, two off the San Gabriel River, and one off the San Diego-Point Loma coast.

FIGURE 2. Three-dimensional plots of 261 surface (a) and bottom (b) temperatures collected during the survey. The line was predicted using a distance–weighted, least-squares method.

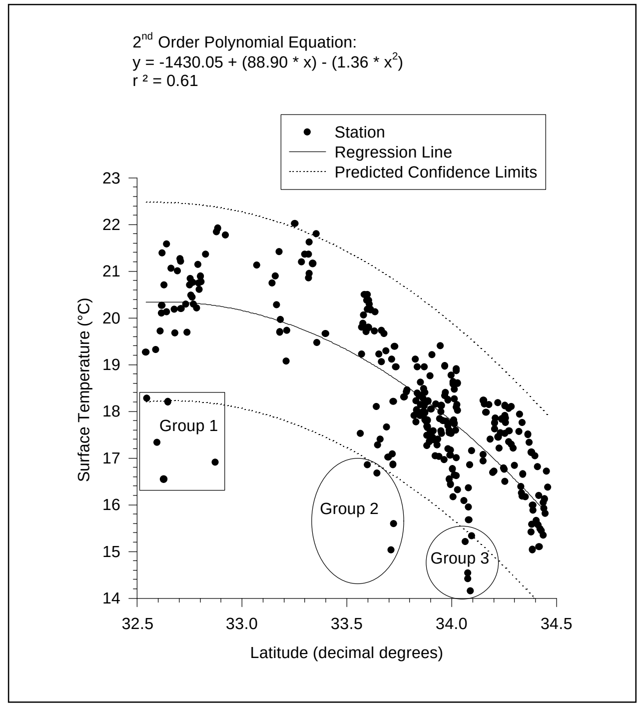


Bottom light transmittance values ranged from 34.8 to 90.0% with a mean of 79.9% (Table 2). A slight increase in transmittance was found with decreasing latitude and increasing depth. Eleven of the 12 lowest values were observed at sites in Group 1 (Figure 15), located in relatively shallow water (14 to 45 m) between the Santa Clara River and Santa Barbara (Figure 16).

DISCUSSION

Three dominant broad-scale patterns were apparent from our survey of the SCB shelf waters. First, surface

FIGURE 3. Surface temperature versus latitude for the 261 sites measured during the survey. A second-order polynomial regression line was fitted through the data with predicted confidence limits for the population. Three groups of outliers were identified: south (Group 1), central (Group 2), and north (Group 3).



water patterns of temperature, salinity, and oxygen were generally dominated by latitudinal relationships. The northern portion of the SCB was colder, lower in salinity, and higher in dissolved oxygen than the southern portion. This pattern is consistent with the effects of the southern-flowing California Current (cold temperatures, low salinity, and high dissolved oxygen), which has its strongest influence on the northern portion of the coast-line. The influence of the California Current, coupled with direct effects from changes in latitude, probably account for the general patterns we observed. However, as the Southern California Countercurrent eddy is formed, the water begins to mix with the northern-flowing California Undercurrent, which contains warm temperatures, high salinity, and low dissolved oxygen (Tibby 1941). This process results in breakdowns similar to those we observed in the general north-to-south trends. This breakdown process was illustrated by our findings of southern areas exhibiting characteristics of water in northern areas.

The second observed pattern was the domination of bottom water properties by a relationship to site depth, with little or no relationship to latitude (Table 2). Deeper waters were the coldest, most saline, and least oxygen-

FIGURE 4. Stations with black squares indicate low surface temperatures relative to surrounding stations in the southern (a), central (b), and northern (c) areas.

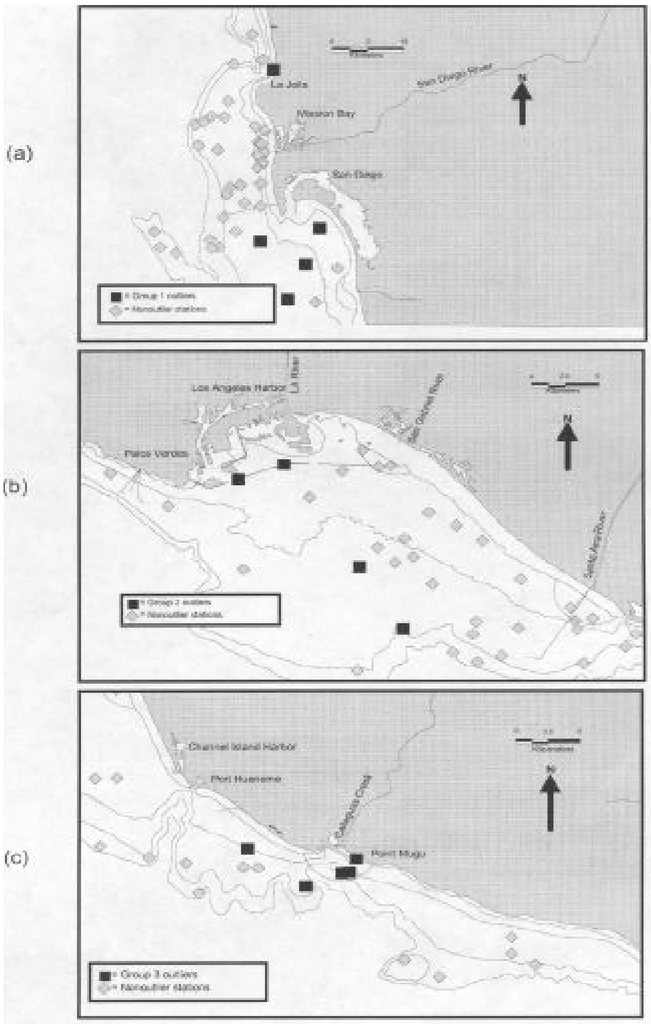


FIGURE 5. Mean water column profile of temperature, salinity, dissolved oxygen, and transmissivity.

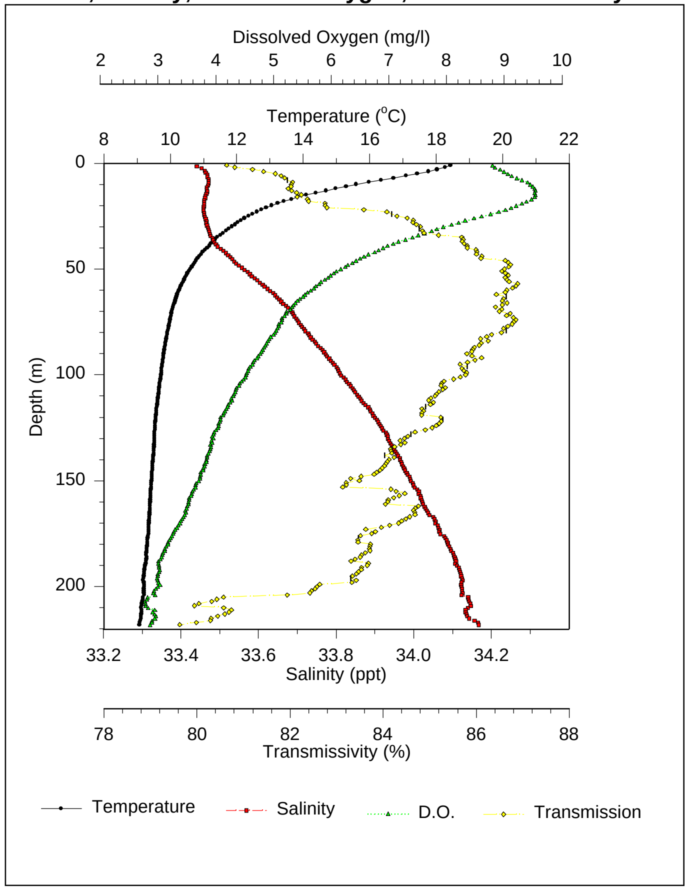
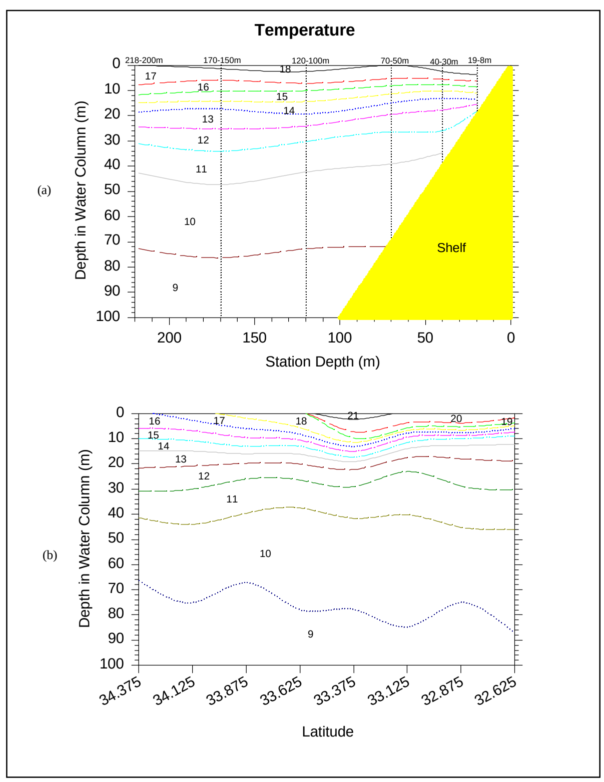


FIGURE 6. Average temperature isopleths representing cross-shore (a) and along-shore (b) portions of the shelf.



ated. This pattern is consistent with general properties of seawater described by previous investigators (Emery 1960, Wooster and Reid 1963, Hickey 1993). While bottom water quality parameters were related to site depth, the relationship was not linear. Two distinct zones of bottom water were defined, with relatively isohaline conditions separating the upper mixed layer from deeper bottom water. Bottom measurements at sites shallower than the bottom of the mixed zone, which generally occurred at approximately 40 m (Figure 11), were secondarily influenced by compressed isotherms (i.e., the thermocline; Figures 6a,b). Other authors (Jackson 1986, Lorenzen 1966) have suggested that this mixed zone can range from the surface to 10-40 m of water depth, depending upon the season and distance from shore (summer being the shallowest depth). Bottom measurements in areas below our observed mixed zone were relatively constant to depths of 200 m. This finding

FIGURE 7. Three-dimensional plots of surface (a) and bottom (b) salinity. The line was predicted using a distance–weighted, least-squares method.

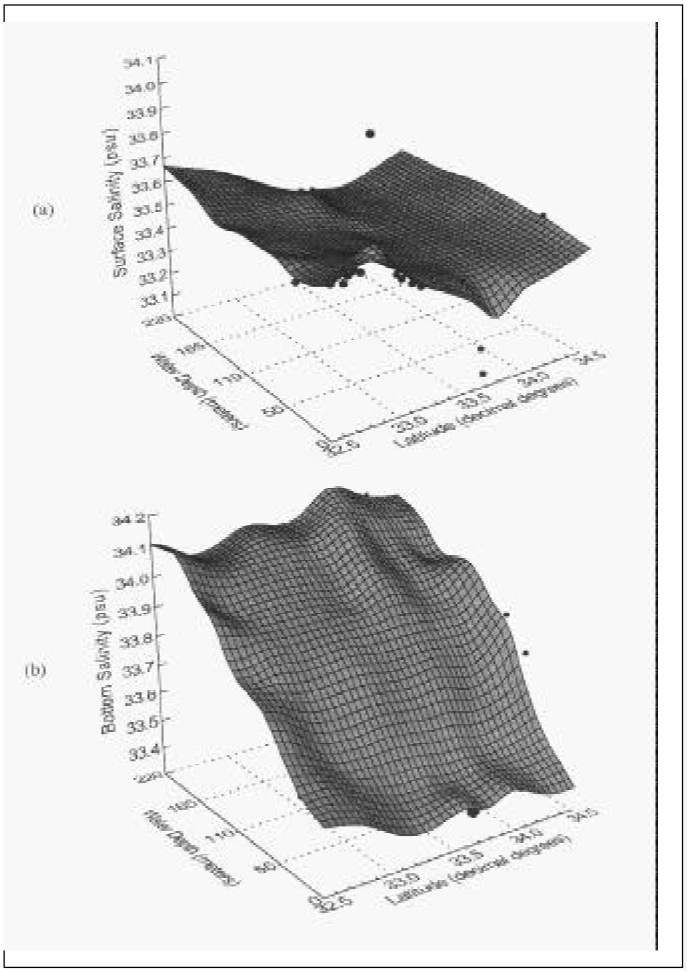


FIGURE 8. Surface salinity versus latitude. A second-order polynomial regression line was fitted through the data with predicted confidence limits for the population.

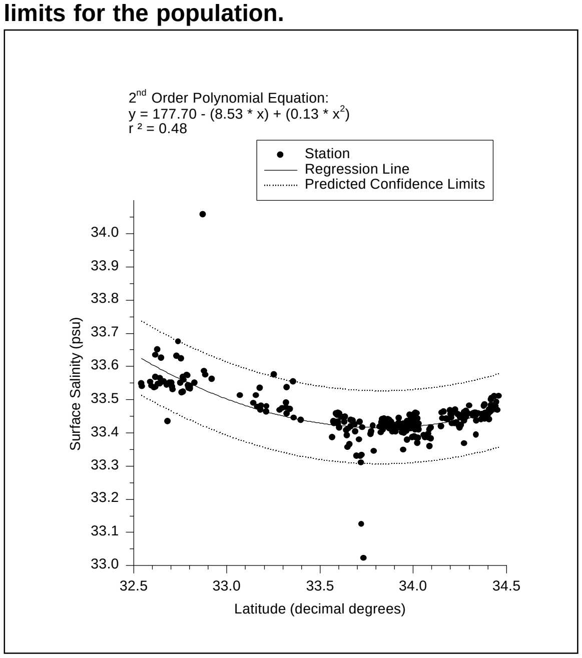
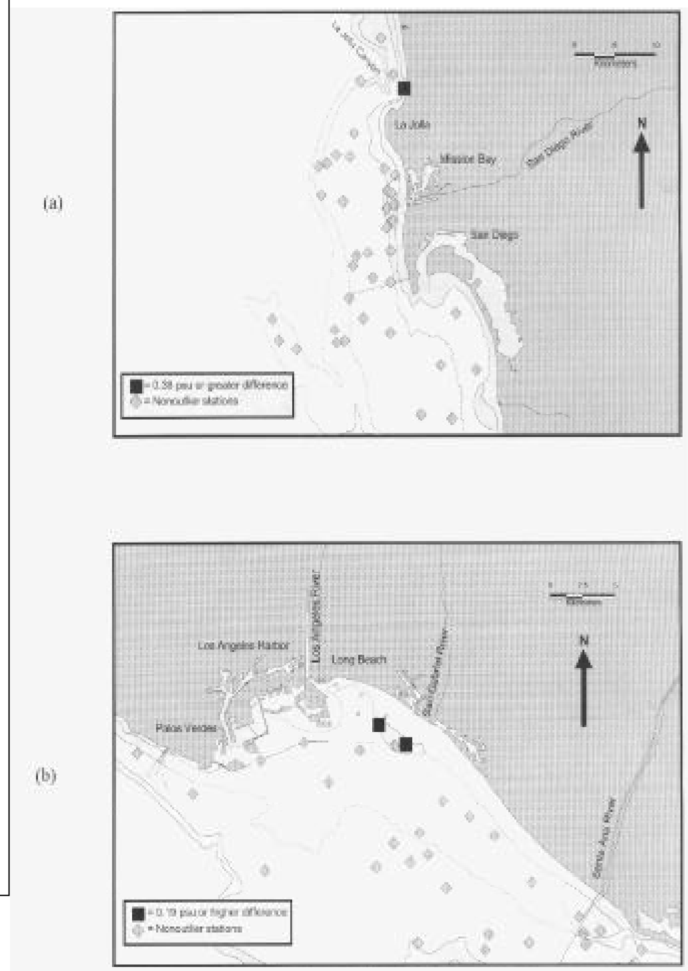


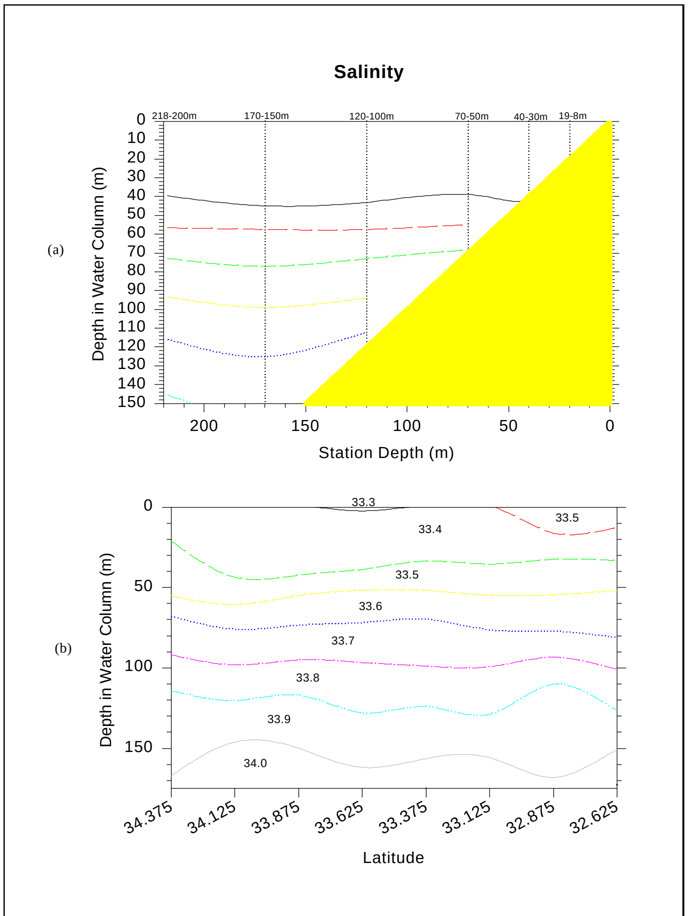
FIGURE 9. Stations with black squares indicate surface salinity outside the confidence range of the relationship with latitude: high surface salinity in the San Diego region (a) and low surface salinity near the Los Angeles and San Gabriel River (b).



suggests that water properties below the mixed zone are influenced by deep offshore oceanographic processes, while those above this thermocline are influenced primarily by surface processes.

The third observed pattern was the presence of a subsurface oxygen maximum layer throughout most of the coastal zone. This layer was confined near or immediately below the thermocline and was closely associated with a subsurface chlorophyll maximum layer (Figure 17). Chlorophyll concentration was derived from fluorescence as measured by an *in situ* fluorometer on one of the CTDs used in the survey. These observations are consistent with those made during offshore CalCOFI surveys (Eppley and Holm-Hansen 1986) and other studies (Cullen *et al.* 1982, Reid *et al.* 1978). These subsurface maxima are seasonally common within the SCB and are typically related to the water column density stratification, paucity of nutrients above a strong

FIGURE 10. Average salinity isopleths representing cross-shore (a) and along-shore (b) portions of the shelf.



pycnocline, and optimal light intensity for photosynthesis (Shulenberger and Reid 1981). Chlorophyll maxima are not typically static, exhibiting motion at tidal and probably internal wave frequencies (Cullen *et al.* 1983, Kamykowski 1973). These forces, coupled with generally weaker thermal stratification, contributed to the erosion or absence of these subsurface oxygen maxima in northern waters.

While most data from this study fit the general patterns described herein, some data exhibited notable exceptions. Although surface dissolved oxygen generally declined moving southward, an area of highly saturated water (>120% and lower temperatures) was observed near the United States-Mexico international border that rivaled northern site concentrations and yielded a hyperbolic appearance in the relationship between oxygen and latitude. Many of these southernmost sites exhibited the low surface temperature, high salinity, and high oxygen pattern that is indicative of more northern sites. This pattern is consistent with reports of a recurring, cold–water, counterclockwise eddy that has been observed in the near-coastal San Diego area (SCCWRP 1985, CSDMWD 1992). As the California Current passes Point Conception and continues equatorward offshore from the United States-Mexico international border, it pushes shoreward as a tongue of low temperature, low salinity water and bends poleward as the Southern California Countercurrent (Lynn *et al.* 1982, Lynn and Simpson 1987). The thermocline at these southern sites was extremely sharp and close to the surface, allowing the oxygen maximum to push much closer to the surface than in other areas. The most likely mechanism influencing this area is coastal upwelling (Dorman and Palmer 1981).

Upwelling events were also observed at three other areas in the SCB (La Jolla Canyon, Point Mugu, and San Pedro Shelf). A localized event (19 m site) over La Jolla Canyon showed surface parameters with low temperature, high salinity (>34.00 psu), and low oxygen. Salinity at this location was typical of water from 120 to 150 m. These measurements suggest that the source is deep water coming up the canyon and surfacing instead of intermediate water, as indicated by the anomalous area south of Point Loma. Sites over Mugu Canyon exhibited low temperatures and high oxygen concentrations, suggesting an upwelling process similar to that observed in the area south of Point Loma. Sites just outside of the breakwater off Los Angeles-Long Beach Harbor exhibited low temperature and low dissolved oxygen. (Figure 4b). Canyons and headlands are known foci of almost continual upwelling patterns, and surface temperature satellite imagery often shows a strong jet of southern-moving cold water originating from Point Fermin.

TABLE 3. R-squared values using second-order polynomials for CTD parameters on latitude and station depth components. Surface and bottom values (261 stations) are presented for the survey on July 12-18, 1994.

	Surface			
	Temperature	Salinity	Dissolved Oxygen	Transmissivity
Latitude	0.612	0.485	0.592	0.022
Depth	0.004	0.010	0.005	0.148
	Bottom			
	Temperature	Salinity	Dissolved Oxygen	Transmissivity
Latitude	0.037	0.013	0.003	0.115
Depth	0.764	0.922	0.875	0.135

FIGURE 11. S-T (salinity-temperature) plot of bottom values showing the bottom boundary layer interaction as depth increases along the shelf.

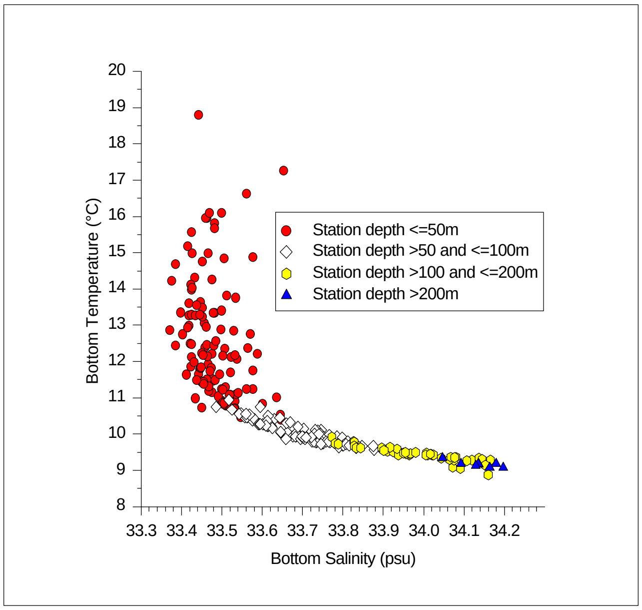
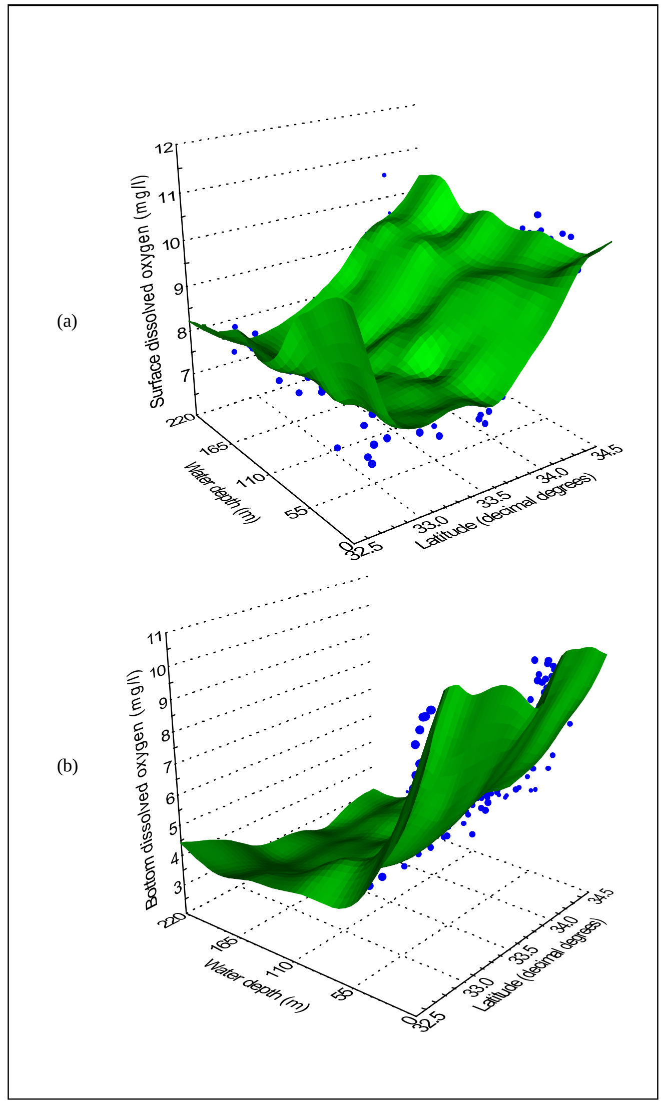


FIGURE 12. Three-dimensional plots of surface (a) and bottom (b) dissolved oxygen values. The line was predicted using a distance–weighted, least-squares method.



Adding to the dynamics of this area is the freshwater input, as noted by low surface salinity, from the Los Angeles and San Gabriel Rivers.

Light transmittance did not follow the spatial patterns exhibited by the other three water column parameters. Surface values increased slightly moving offshore and bottom values decreased slightly moving north, but both patterns were highly variable. The most pronounced response was that of low bottom light transmittance in the area between the Santa Clara River and Santa Barbara. This pocket of low light transmittance may be a result of resuspension events in two fine sediment areas, the Santa Clara Prodelta Deposit and the Las Pitas Mud Deposit. Topographical conditions, river input, and southward surface currents in the channel nearshore can cause an eddy to form within this broad shelf area, resuspending light-weight particles in the area. Future regional surveys will incorporate fluorometry as part of the CTD package to allow better distinction between sediment resuspension and biological activity in the interpretation of transmittance data.

In this study, we have provided the first temporally constrained study of coastal SCB water quality properties. Many of the oceanographic phenomena described herein corroborate findings from previous studies of waters over the basins. This study further described small-scale events such as localized upwelling, riverine inputs, and sediment resuspension, which to date have not been adequately described. Additional study is required to better understand these processes and their effects upon or interactions with the anthropogenic inputs that dominate the southern California coastal environment. Future studies are also needed to understand the time parameters within which these processes occur. These observations add to the body of knowledge on shelf dynamics and provide a valuable baseline from which to continue investigation. These continued surveys present the opportunity to work in a collaborative effort with the CalCOFI quarterly surveys and further our understanding of SCB oceanographic processes, both over the basins and shelf areas.

FIGURE 13. Surface percent oxygen saturation values versus latitude. The line represents a second-order polynomial regression with predicted confidence limits for the population. The grouped outliers represent those identified in Figure 3: south (Group 1) and north (Group 3).

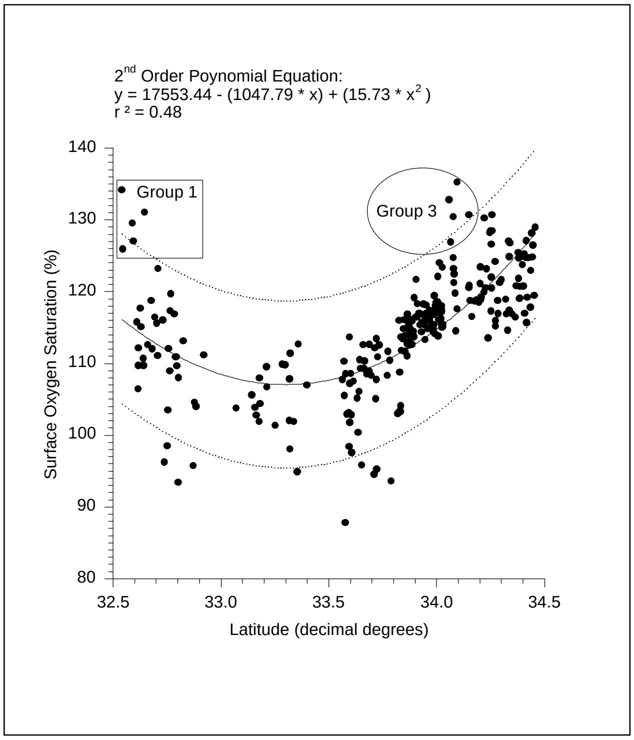


FIGURE 14. Average oxygen isopleths representing cross-shore (a) and along-shore (b) portions of the shelf.

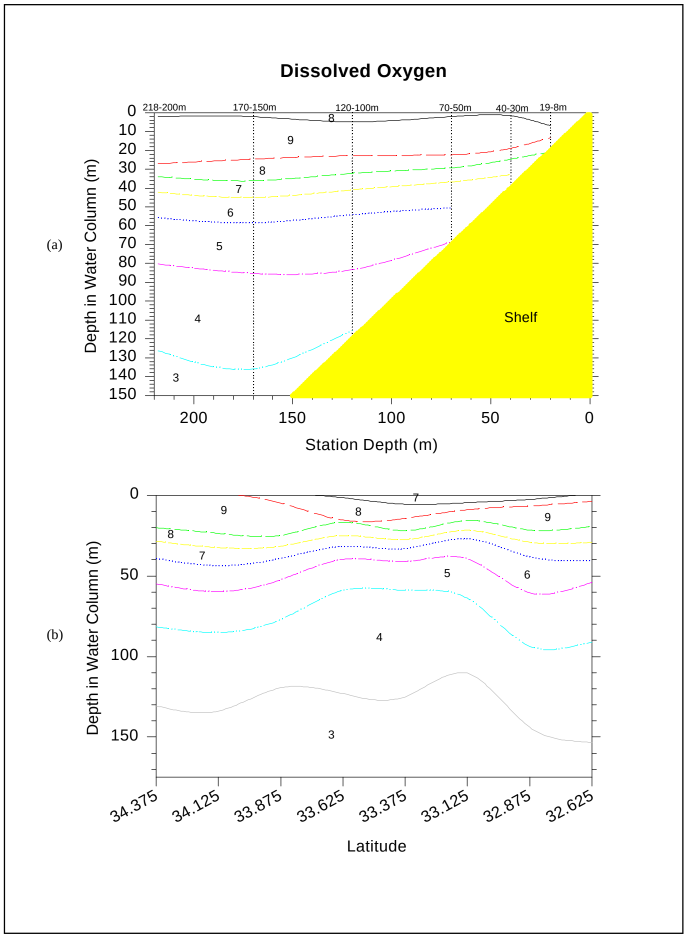


FIGURE 15. Bottom transmissivity versus latitude. The line represents a second-order polynomial regression with predicted confidence limits for the population. The circled points represent a group of outliers found in the northern part of the study area.

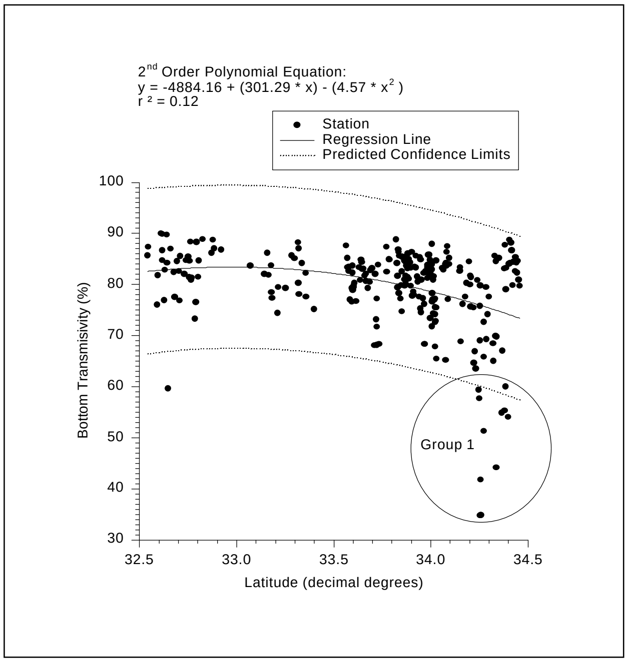


FIGURE 16. Stations with black squares indicate those with bottom light transmittance outside the confidence range of the relationship with latitude.

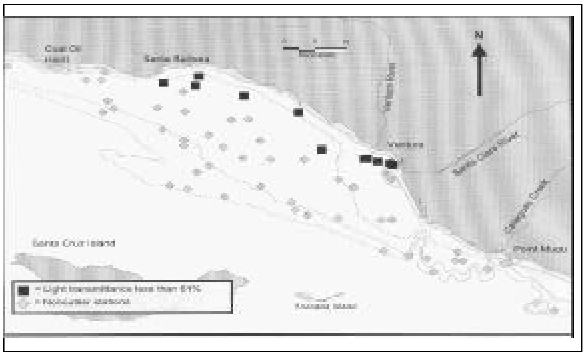
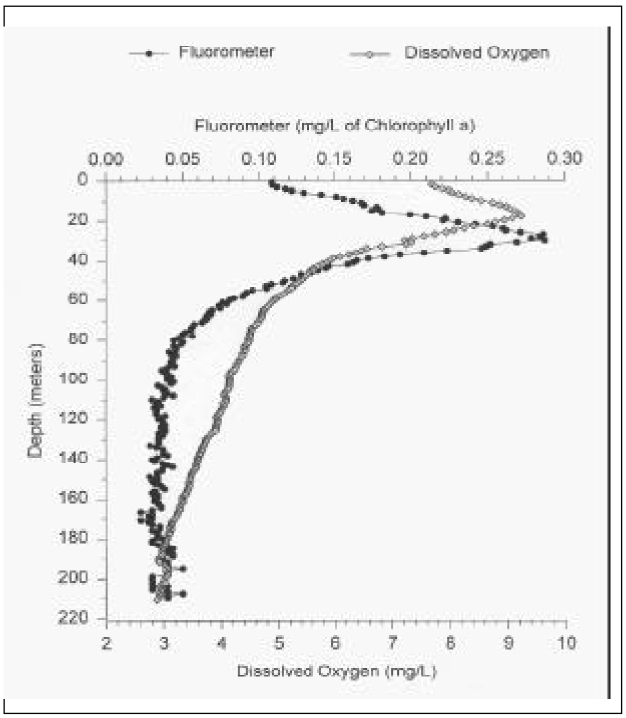


FIGURE 17. Mean water column profile of fluorometer and dissolved oxygen for Region 4 of the survey (see Figure 1).



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