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Surface Manifestations of Subsurface Thermal Structure in the California Current

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Remote sensing is useful for studying certain oceanographic problems only if the signal obtained from the sea surface contains information about subsurface structure. Historical bottle temperature data from the California Current were analyzed for surface manifestations of vertical structure and subsurface mesoscale structure. Results showed that surface temperature is useful in predicting thermocline strength over a large area south of Point Conception: the error of a regression estimate is 20–30% less than the error of the seasonal mean. However, surface temperature gives little useful information about mixed layer depth. Mesoscale patterns of temperature at the surface and at depth (caused by eddies, meanders and upwelling) are coherent ($r^2 > 0.50$) to a depth below the mixed layer only off central California and Point Conception and along the coast of Baja California. Coherence is most likely to extend below the mixed layer during summer, when the water column is strongly stratified and the mixed layer is most shallow. Thus some aspects of subsurface structure, within limited regions of the California Current, have surface manifestations potentially detectable by satellite sensors.

1. INTRODUCTION

Satellite sensors have revolutionized oceanography in the past decade by providing repetitive and synoptic measurements of temperature, color, winds, and currents over large areas of the sea surface. Sea truth validation of satellite estimates of surface parameters has led to sensor and algorithm refinements that have reduced errors to acceptable levels for many applications. However, for studies of structure and processes below the sea surface, even error-free satellite data are useful only if the surface signal contains information about subsurface structure. For example, in an expendable bathythermograph (XBT) survey across the central north Atlantic [*Dugan* 1980], an unambiguous surface temperature signal was detected for only one of four cold-core eddies observed in the permanent thermocline. A thermocline front had no corresponding surface temperature signal, while a surface thermal front did not extend into the thermocline. From a global survey of sea surface temperature (SST) fronts detected by satellite, *Legeckis* [1978] concluded that isothermal surface layers obscure subsurface horizontal temperature gradients in tropical oceans year-round and in subtropical oceans during summer.

Satellite infrared temperature data have been used increasingly in studies of the California Current system as the importance of mesoscale variability has become more apparent [*Bernstein et al.*, 1976; *Koblinsky et al.*, 1984; *Flament et al.*, 1985]. Above 500 m, this system consists of (1) a broad equatorward California Current with a low-salinity core about 400 km offshore, (2) a poleward California Undercurrent with a core at ~300-m depth over the continental slope, and (3) a fall-winter poleward California Countercurrent at the surface within 150 km of the coast [*Simpson et al.*, 1986]. Mesoscale coastal jets or streamers and offshore eddies are much more energetic than the large-scale mean surface flows, as is generally true in eastern boundary currents [*Wyrtki et al.*, 1976].

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The California Cooperative Oceanic Fisheries Investigations (CalCOFI) program has sampled standard depths at stations covering most of the California Current system since 1950 (Figure 1). Gross vertical structure parameters such as mixed layer depth, thermocline depth, and stratification or stability can be derived from CalCOFI temperature data. Although the 37- to 74-km spacing of CalCOFI stations may barely resolve mesoscale eddies, meanders in the core of the California Current, and coastal upwelling, such features are clearly visible in maps of cruise data [*Wyllie*, 1966].

In this paper I analyze a large set of CalCOFI hydrographic data to answer two basic questions about the utility of remotely sensed surface data in the California Current: (1) Can information about vertical structure below the surface be derived from surface temperature? (2) Are mesoscale patterns of surface temperature coherent with patterns below the mixed layer or thermocline?

Surface data will be considered useful in estimating subsurface structure (question 1) if they can produce an estimate that is more precise than an estimate based on climatology alone (i.e., if the standard error of the regression estimate is less than the standard deviation around annual or seasonal station means). Vertical coherence of mesoscale patterns (question 2) was examined within regions with dimensions of 100–400 km to exclude larger-scale latitudinal and onshore-offshore patterns. Variability of temperature at standard depths within regions represents effects of offshore eddies, California Current meanders, coastal upwelling, and other structures and processes resolved by the station grid. Correlation between the surface and depth is a measure of the coherence of mesoscale surface structure with depth. Alternatively, it is a measure of the contribution of subsurface structure to the surface temperature signal.

The practical utility of estimates of subsurface structure derived from surface observations will depend on the particular problem at hand. This empirical analysis is intended to explore the potential and limitations of extrapolating accurate remotely sensed surface data into the water column. Errors introduced into the surface signal at the air-water interface, in the atmosphere, and by the sensor are not considered here.

2. METHODS

The CalCOFI data set includes temperature at 14 standard depths (0, 10, 20, 30, 50, 75, 100, 125, 150, 200, 250, 300, 400, and

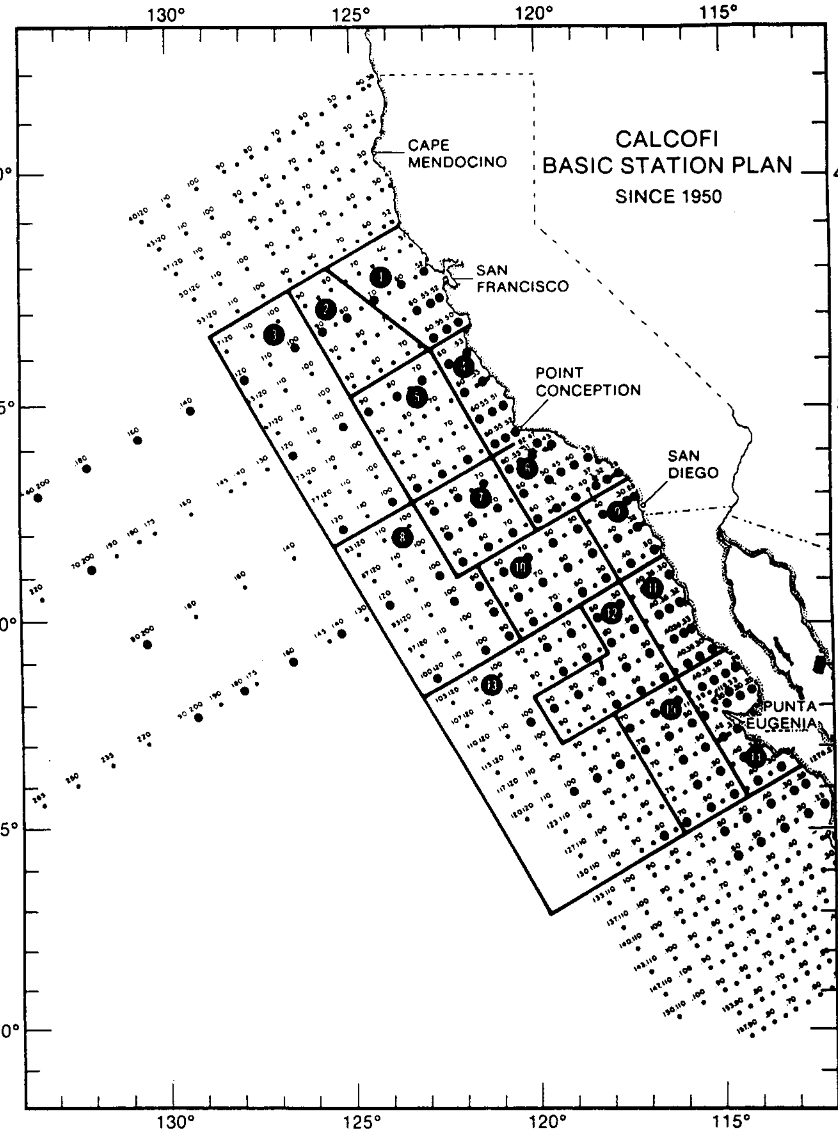

Fig. 1. CalCOFI station grid. Only the most frequently sampled stations (large dots) on cardinal lines 60, 70, 80, 90, 100, 110, 120, and 130, out to station 120, were used in the verical structure analysis. Regions for the correlation analysis are named as follows: 1, central California coastal; 2, central California transition; 3, central California oceanic; 4, Point Conception coastal; 5, Point Conception transition; 6, southern California coastal; 7, southern California transition; 8, southern California oceanic; 9, border coastal; 10, border transition; 11, northern Baja California coastal; 12, northern Baja California transition; 13, northern Baja California oceanic; 14, Punta Eugenia coastal; 15, Punta Eugenia transition.

500 m) from subsets of the basic station grid (Figure 1) occupied on 200 cruises from February 1950 to October 1984 (7–231 stations per cruise).

2.1. *Vertical Structure*

Three vertical structure parameters were estimated from discrete temperature profiles. Thermocline strength ($|\Delta T/\Delta z|$) was calculated in the depth interval with the maximum vertical temperature gradient. Location of the thermocline depth within this interval was weighted by the temperature gradients above and below the interval. Mixed layer depth was calculated as the depth at which temperature extrapolated from the apparent thermocline equaled surface temperature [*Wyrtki,* 1971]. Thus mixed layer depth is always less than the thermocline depth.

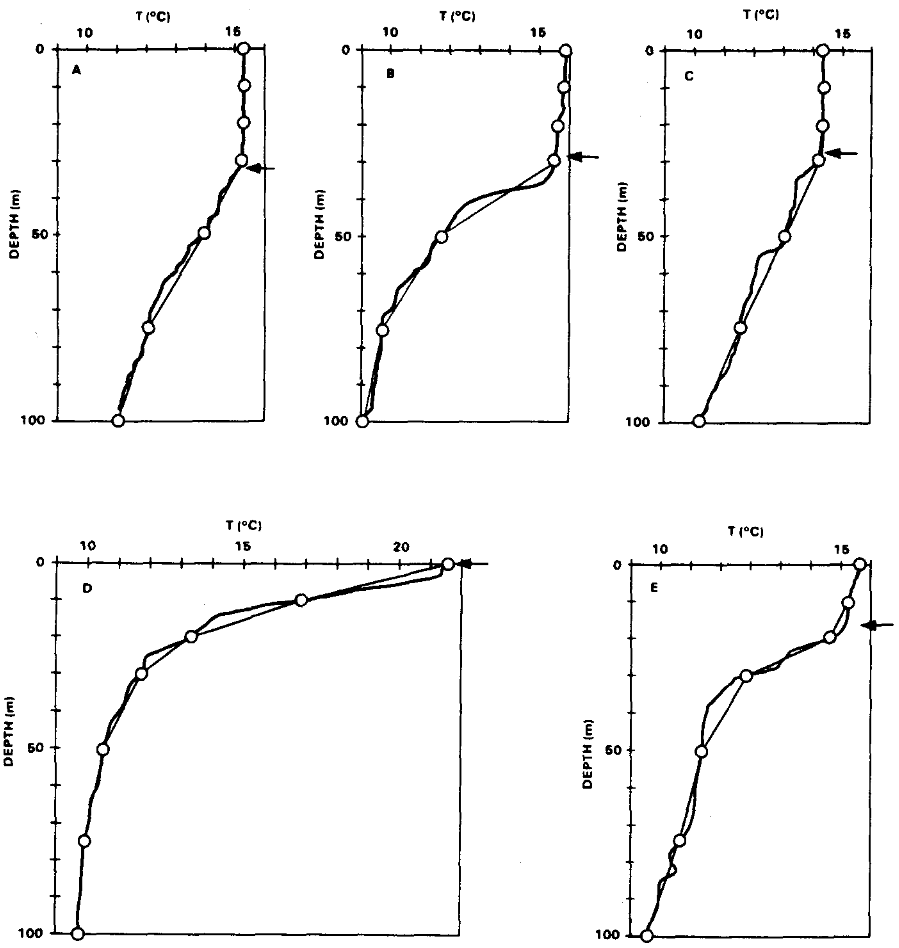

Fig. 2. A variety of CTD temperature profiles from the Southern California coastal region (Figure 1) compared to the profiles that would be observed with standard CalCOFI bottle samples at 0, 10, 20, 30, 50, 75, and 100 m. Mixed layer depths (arrows) are calculated from the discrete profiles as described in the text. CTD data were provided by R. Lynn.

CalCOFI bottle samples cannot completely describe the vertical structure seen in continuous temperature profiles (Figure 2). Thermocline strength is underestimated (e.g., Figure 2*b*). Fine-scale features such as steps and inversions are not resolved (Figures 2*c* and 2*e*). Mixed layer depth may be estimated accurately (Figures 2*a* and 2*c*) or not (Figure 2*b*). About 10% of the stations, for which the bottle data gave a mixed layer depth of ≤ 0 m (Figure 2*d*) or a thermocline in the deepest interval of the cast were considered to be inadequately described by bottle samples and were omitted from the analysis.

Linear regression relationships between surface temperature and vertical structure parameters were calculated at 68 cardinal stations occupied >20 times (Figure 1). Utility of the relationships was measured by ratios of the rms error about the regression line to the standard deviation and to the mean of the dependent variable. The first ratio will be called the relative rms error. For large *n*, as in this analysis, the relative rms error is equal to the square root of the ratio of the residual sum of squares to the total sum of squares, or the square root of $(1 - r^2)$. The second ratio (rms error/mean) is a coefficient of error, or residual variation, analogous to the coefficient of variation.

2.2. *Vertical Coherence of Mesoscale Structure*

Mesoscale regions are delimited in Figure 1. The alongshore boundaries roughly define a transition zone between coastal and oceanic domains [*Simpson et al.*, 1986]. Regional correlations of temperature at 0 m and at depth were calculated from sums of squares within cruises to eliminate variance and covariance between cruises (seasonal and interannual variability). Decorrelation depth is defined as the depth at which correlation with the surface equals 0.71 (r^2=0.50), calculated by linear interpolation between standard depths. Mean thermocline depth and mixed layer depth, as defined above, were calculated for each region and season. Differences between decorrelation depth and mixed layer

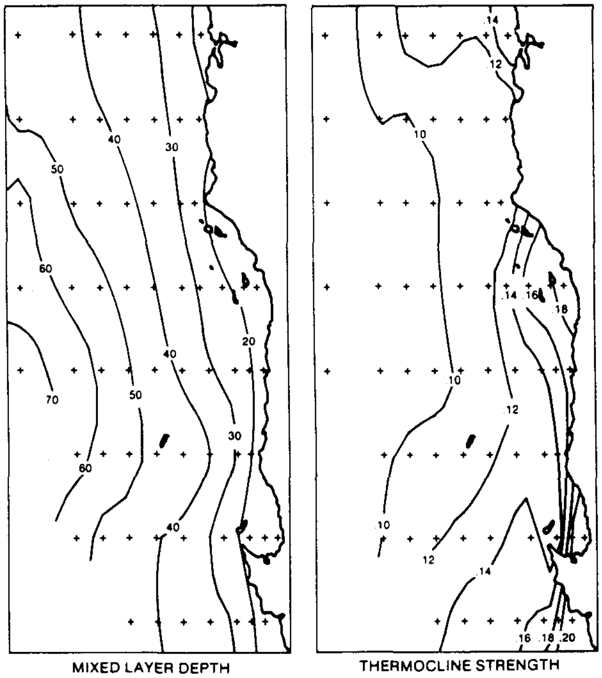

Fig. 3. Mean mixed layer depth (in meters) and thermocline strength (in degrees Celsius per meter) at 68 CalCOFI cardinal stations off California and Baja California, 1950–1984.

or thermocline depth were tested by the t-test [*Sokal and Rohlf*, 1969] using the null hypothesis that r=0.71 at the mixed layer or thermocline depth.

3. Results

3.1. *Vertical Structure*

The mean mixed layer deepens and the thermocline weakens from nearshore to offshore stations (Figure 3). Mixed layer and thermocline depths are strongly correlated (Figure 4, r=0.933, n=6144). The steplike distribution of points in the scatter plot is an artifact of the discrete bottle spacing. Both features are most shallow nearshore between Point Conception and Punta Eugenia and are correlated with thermocline strength (r=–0.34 for mixed layer depth and r=–0.43 for thermocline depth). The thermocline is strongest in two nearshore areas: the Southern California Bight and south of Punta Eugenia.

Since mixed layer depth and thermocline depth are so closely related, only mixed layer depth and thermocline strength were considered as functions of surface temperature. Regressions of these two vertical structure parameters on surface temperature are summarized in Table 1. Overall regression relationships are statistically significant ($P[r=0] << 0.001$ by the F-test; Figure 5). For both parameters, r^2 calculated within stations is greater than the overall value. R^2 calculated within stations and seasons is less than the overall value, perhaps because of small ranges of the independent variable at some stations in some seasons.

Spatial patterns of relative rms error about the seasonal station regression lines are illustrated in Figure 6. Regression on surface temperature gives an estimate of mixed layer depth with less error than that of the seasonal mean only in a small region offshore of Punta Eugenia. Regression on surface temperature gives an estimate of thermocline strength with an error 20–30% less than that of the seasonal mean in a large area south of Point Conception. The coefficient of error (rms error/mean) of the estimates at these 50 southern stations is 0.34 (±0.27). North of Point Conception and at the offshore edge of the station grid, the regression estimate of thermocline strength is no more precise than the seasonal mean at a station.

3.2. *Vertical Coherence of Mesoscale Structure*

Profiles of the correlation of surface temperature with temperature at depth in coastal, transition, and oceanic regions are shown in Figure 7. The decorrelation depth (r^2=0.50) is often significantly deeper than the mixed layer in regions off central California and Point Conception and in coastal regions off Baja California (Table 2). The decorrelation depth is most likely to be deeper than the mixed layer in summer, when the water column is strongly stratified and the mixed layer is most shallow. In contrast, the decorrelation depth tends to be significantly more shallow than the mixed layer in regions offshore of Baja California, where the mixed layer is deepest. Among 15 regions and 4 seasons (60 cases), the decorrelation depth is deeper than the mixed layer in 26 cases (r=0.83±0.04 at the mixed layer depth), not significantly different in 23 cases (r=0.71±0.04), and more shallow in 11 cases (r=0.55±0.04).

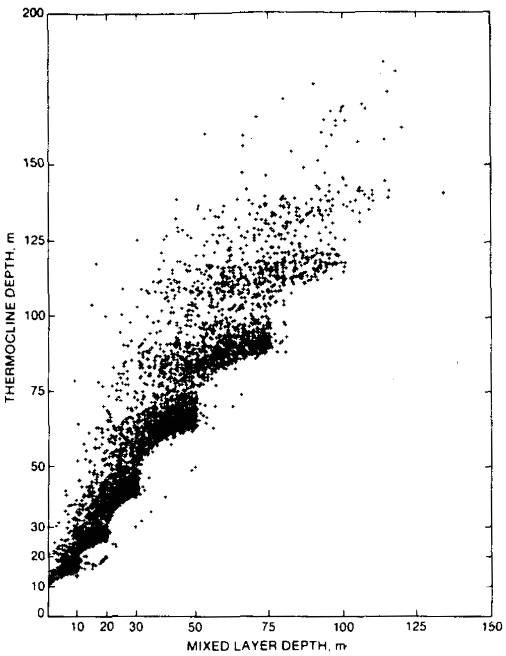

Fig. 4. Thermocline depth versus mixed layer depth at 68 CalCOFI cardinal stations, 1950–1984.

4. DISCUSSION

4.1. *Vertical Structure*

In the CalCOFI data set, mixed layer depth cannot be derived from surface temperature by linear regression; the deepest mixed layers are found at stations with intermediate surface temperatures (Figure 5). Shoaling of the thermocline can be associated with either warming or cooling by (1) seasonal warming and stratification of the surface layer or (2) upwelling of colder, deeper water caused by offshore transport of warm surface water. In either case, shoaling will occur when winds are too weak to produce enough vertical shear to overcome stratification at the bottom of the mixed layer. Upwelling is a coastal, spring-summer phenomenon, and seasonal warming peaks in late summer or early fall. It should be possible to separate these effects using season- and station-specific regressions, but the results summarized in Table 1 show that on average, there is no gain in precision (r^2 decreases when calculated within stations and seasons).

Figure 8 illustrates relationships at CalCOFI station 90.70, located ~300 km west of San Diego. Although the station is beyond the immediate influence of coastal upwelling, the regression of mixed layer depth on surface temperature is significant only for summer ($r^2 = 0.21$). Mean summer mixed layer depth is 31.2 m with a standard error of 14.0 m, while the rms error about the regression line is 12.6 m, only 10% less than the standard error. An exceptionally large improvement is realized at station 120.90: in summer, mean mixed layer depth is 37.6 m with a standard error of 22.7 m, while the regression rms error is 14.0 m, an improvement of 38%. Generally, however, surface temperature does not give useful information about mixed layer depth even using regression relationships specific for each season at each station.

In contrast to mixed layer depth, thermocline strength is strongly related to surface temperature (Figures 5 and 6, Table 1), because thermocline strength is essentially the difference between the temperature of the surface layer and the relatively constant temperature of the deep layer below the seasonal thermocline. At station 90.70 (Figure 8), regressions for winter, spring, and summer are significant (r^2 = 0.34, 0.27, and 0.33, respectively). While mean spring surface temperature (14.55°C) is only slightly less than mean winter surface temperature (14.69°C), the regression intercepts are different: at the same temperature, thermocline strength in winter is 20% greater than thermocline strength in spring. This illustrates the value of season-specific regressions. In fall, regression between thermocline strength and surface temperature is not significant. Very large thermocline gradients exist without a rise in surface temperature.

South of Point Conception and within 300–500 km of the coast, regression on surface temperature gives an estimate of thermocline strength that is 20–40% more precise than an estimate equal to the seasonal mean. For example, at station 110.70, summer thermocline strength estimated from the climatological mean is 0.109 ± 0.040°C m^{-1}. From an observed surface temperature of 19.0°C (0.4°C above the mean), one could estimate with equal confidence that the thermocline strength is 0.166 + 0.029°C m^{-1}.

Thermocline strength is most strongly related to surface temperature in the Southern California Bight, in shallow coastal waters north and south of Punta Eugenia, and in a band parallel to the coast ~200 km off Punta Eugenia (areas within the 0.70 contour of relative rms error, Figure 6). Circulation in the Southern California Bight is dominated by the semiclosed southern California eddy. Bahia Sebastian Vizcaino, to the north of Punta Eugenia, is likewise isolated from the large-scale flow of the California Current and Inshore Countercurrent. Thus local forcing at the surface may have a greater effect on subsurface structure in these coastal regions. The band offshore of Punta Eugenia is characterized by complex meanders in the core of the California Current and a recurrent anticyclonic eddy near Guadalupe Island [*Lynn et al.*, 1982]. Attenuation of the California Current may increase the relative impact of local forcing in this region as well.

4.2. *Vertical Coherence of Mesoscale Structure*

Temperature patterns at depths below the mixed layer are coherent with surface temperature patterns ($r^2 > 0.50$) in coastal, transition, and oceanic regions off central California and Point Conception and in coastal regions off northern Baja California and Punta Eugenia (Table 2). Coherence to a depth below the mixed layer occurs most frequently in regions with shallow mixed layers, but it occasionally occurs in oceanic regions with deeper mixed

TABLE 1. R^2 Values for Linear Regressions on Surface Temperature

	Mixed Layer Depth	Thermocline Strength
Overall	0.024	0.200
Within stations	0.153	0.267
Within stations and seasons	0.005	0.102

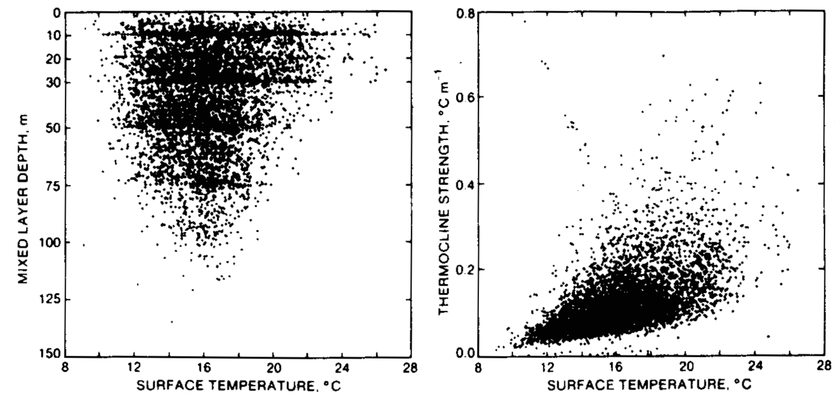

Fig. 5. (Left) mixed layer depth versus surface temperature and (right) thermocline strength versus surface temperature at 68 CalCOFI cardinal stations, 1950–1968.

layers. In other cases, r^2 falls below 0.50 within the mixed layer and to a value as low as 0.24 at the mixed layer depth.

Correlation is a simple way to compare surface and subsurface patterns, but may underestimate the value of surface patterns as manifestations of subsurface structure. For example, *Simpson et al.* [1984] used sea surface temperature imagery in a study of a three-layer eddy in the transition zone off Point Conception. The subsurface warm-core eddy was clearly manifested as a warm

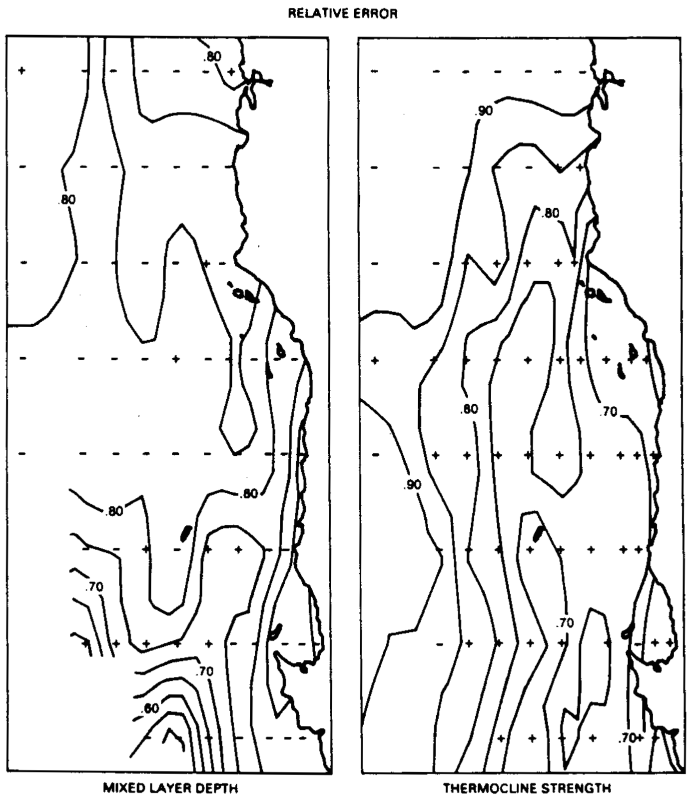

Fig. 6. Relative rms error of estimates of mixed layer depth and thermocline strength from regression on surface temperature (plus signs) or from the seasonal station mean (minus signs, where the regression estimate is no more precise than the seasonal mean).

patch at the surface, but there was a cold-core layer at 75-175 m between the eddy and the warm surface layer. Although the anticyclonic flow of the eddy was coherent to ~1000 m, correlation with the surface temperature pattern dropped to zero in the cold-core layer [*Simpson et al.*, 1986].

Surface-subsurface temperature correlation profiles show two basic patterns in the CalCOFI data set: (1) a monotonic decrease of *r* with depth or (2) a minimum *r* at an intermediate depth between 50 and 125 m (Figure 7). Correlation minima occur year-round at

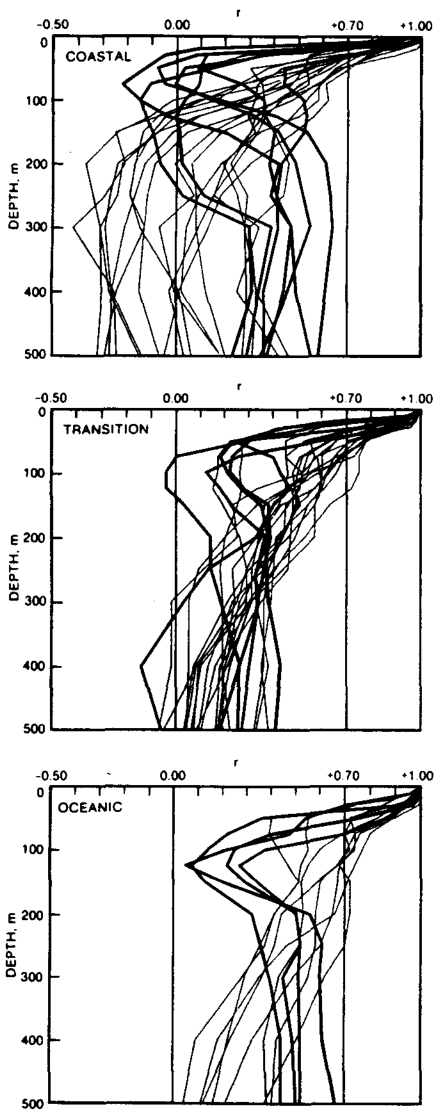

Fig. 7. Temperature correlation profiles (correlation of surface temperature with temperature at depth, within cruises), by region and season, from 1950-1984 CalCOFI data. Heavy lines are profiles with a minumum *r* value that is significantly less than at least one *r* value at a greater depth.

TABLE 2. Temperature Decorrelation Depth and Mixed Layer Depth by Region and Season

	Winter	Spring	Summer	Fall
Central California				
Coastal				
Decorrelation depth	32--	51+	21+++	35+++
Mixed layer depth	41	26	14	19
Transition				
Decorrelation depth	55	79+	45+++	35
Mixed layer depth	47	44	24	27
Oceanic				
Decorrelation depth	114+	251	111++	107+
Mixed layer depth	59	65	30	33
Point Conception				
Coastal				
Decorrelation depth	27---	30	30+++	27++
Mixed layer depth	36	27	18	22
Transition				
Decorrelation depth	130++	71++	49	38+
Mixed layer depth	48	48	29	30
Southern California				
Coastal				
Decorrelation depth	30	20---	15+	16
Mixed layer depth	31	24	14	16
Transition				
Decorrelation depth	64	67	44+++	32
Mixed layer depth	53	55	34	31
Oceanic				
Decorrelation depth	158+++	74	34-	38
Mixed layer depth	70	73	46	41
Border				
Coastal				
Decorrelation depth	32	14---	11	16
Mixed layer depth	30	17	11	15
Transition				
Decorrelation depth	46	44	18---	23---
Mixed layer depth	48	47	25	29
Northern Baja California				
Coastal				
Decorrelation depth	47++	46+++	34+++	30+++
Mixed layer depth	35	26	15	18
Transition				
Decorrelation depth	55	45--	24---	32
Mixed layer depth	56	58	31	31
Oceanic				
Decorrelation depth	54---	75	31	37
Mixed layer depth	66	68	36	36
Punta Eugenia				
Coastal				
Decorrelation depth	46+++	41+++	18+++	29+++
Mixed layer depth	33	24	13	16
Transition				
Decorrelation depth	44--	72++	25+	24
Mixed layer depth	49	49	22	25

Symbols denote $P(r^2=0.50$ at mixed layer depth); +, $P<0.05$; ++, $P<0.01$; +++, $P<0.001$. Plus signs mean that decorrelation depth is deeper than mixed layer depth; minus signs mean that decorrelation depth is more shallow than mixed layer depth.

50-75 m in the southern California coastal region and in spring, summer, and fall at 75-125 m in the border coastal region. These correlation minima occur below the thermocline, the strength of which is very strongly related to surface temperature in the

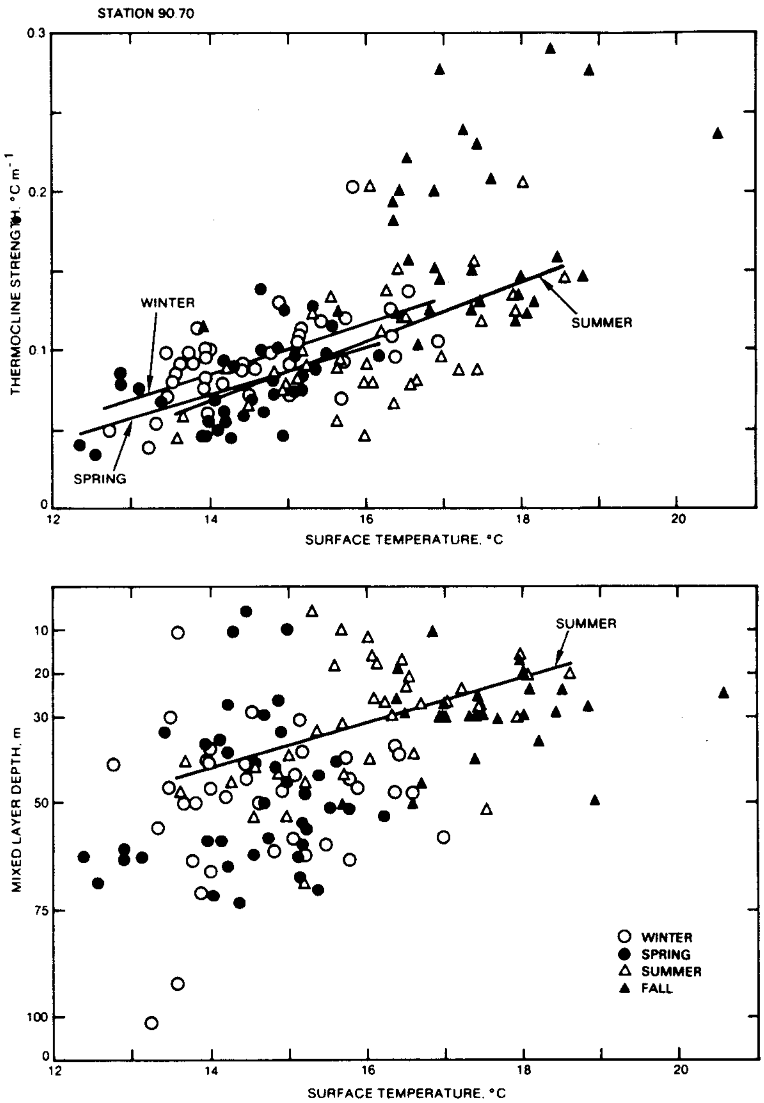

Fig. 8. (Top) mixed layer depth versus surface temperature and (bottom) thermocline strength versus surface temperature at CalCOFI station 90.70. Significant seasonal regression lines are indicated.

Southern California Bight. The flow of the California Undercurrent in these regions is coherent with the surface Inshore Countercurrent, but properties like temperature may be uncorrelated because the source waters of these currents are different (warm, salty equatorial Pacific water and cold, low-salinity subarctic Pacific water, respectively, [*Lynn and Simpson,* 1987]). The most problematic aspect of correlation minima at intermediate depths is the increase in correlation with the surface at greater depths. A single realization of such a profile might be caused by an intrusion of a different water type at the intermediate depth, but long-term mean profiles of that shape are more difficult to explain.

Correlation minima also occur year-round at 125 m in the northern Baja California oceanic region. An offshore, secondary peak in California Current flow occurs in the upper 100–150 m in this region [*Lynn and Simpson,* 1987]. Finally, correlation minima occasionally occur at 50–125 m in transition regions south of Point Conception: southern California and border in fall, northern Baja California in summer and fall, and Punta Eugenia in winter. The core of the California Current is found in these regions, but flow and distributions of properties in the surface layer are modified by mesoscale eddies [*Lynn and Simpson,* 1987]. Three-layer eddies, such as the one observed by *Simpson et al.* [1984], may be responsible for the shape of these correlation profiles.

5. CONCLUSIONS

Satellite imagery has proven its value in a wide range of applications, mostly limited to the surface layer of the ocean [cf. *Fiedler et al.,* 1984; *Felsher,* 1986]. Analysis of the CalCOFI data set demonstrates that sea surface data, as might be obtained by accurate remote sensing techniques, can provide some useful information about mesoscale structure in the surface layer above the seasonal thermocline and about the vertical structure of the water column through the thermocline.

Linear correlation analysis of the vertical coherence of mesoscale structure can only show that surface imagery provides information about thermocline fronts, subsurface eddies, or undercurrents where those features are coherent with surface layer fronts, eddies, or currents. The value of surface imagery used in this way requires prior knowledge based on surface and subsurface sampling. The California Current is a relatively well known system; great care must be taken when using remote sensing data to infer subsurface structure in less well known systems.

In the California Current, surface temperature provides some limited information about vertical thermal structure and subsurface mesoscale structure. Errors introduced into the temperature signal at the sea surface, in the atmosphere, and on board the satellite will further limit the utility of the data. In the future, measurements of sea surface winds from satellite scatterometers or ocean color from new color sensors may offer information complementary to sea surface temperature that would improve the precision of derived estimates of vertical structure parameters. Satellite sensors will be fully exploited for global, regional, and mesoscale studies of the marine environment when subsurface information can be reliably derived from satellite data.

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