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YEAR-TO-YEAR FLUCTUATIONS OF THE CALIFORNIA COUNTERCURRENT AND EFFECTS ON MARINE ORGANISMS

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ABSTRACT

Interannual fluctuations of alongshore currents off California can be inferred from fluctuations of dynamic height at a nearshore, deepwater station in Monterey Bay (station H-3) and from sea level at coastal tide gages. Hydrographic data for the period 1969 to 1978 at station H-3 show anomalous depressions of the 8° to 12°C isotherms by as much as 100 m during some years. The depressions are associated with anomalous elevations of dynamic height and sea level, and appear to occur in a double wave, one in summer and a second the following fall or winter. The anomalous depressions are apparently caused by two processes: (1) a remote forcing caused by propagation of coastal trapped waves poleward from El Niño conditions in the tropics and (2) a local forcing caused by anomalously strong onshore Ekman transport.

By geostrophy, anomalous elevations of the sea surface along the coast are associated with anomalous increases in northward alongshore currents. These increases in northward flow have a variety of effects on marine organisms, including range extensions of plankton and anomalous shifts of salmon's migration routes.

RESUMEN

Las fluctuaciones anuales en las corrientes costeras de California pueden determinarse mediante los datos obtenidos de varias fuentes; la elevación dinámica cerca de la costa, información obtenida en la estación localizada en aguas profundas de la Bahía de Monterey (Estación H-3), y los mareógrafos costeros. Los datos hidrográficos correspondientes al período de 1969 a 1978 en la Estación H-3 indican que durante algunos años se produce un descenso de las isotermas de 8° y de 12°C hasta los 100 m. de profundidad. Estos descensos están asociados con elevaciones dinámicas anómalas y del nivel del mar, presentándose una ondulación doble, una onda para el verano y otra a continuación en otoño o invierno. Estos descensos anómalos son aparentemente el resultado de dos procesos, uno local, ocasionado por el transporte Ekman, fuerte y anómalo hacia la costa, y otro con la acción alejada de esta región y en relación con el fenómeno del Niño en el trópico, produciendo la propagación hacia el polo de las olas atrapadas en la zona costera.

Elevaciones geostróficas anómalas de la superficie del mar a lo largo de la costa, están asociadas con incrementos también anómalos en la progresión de las corrientes costeras hacia el norte. Estos aumentos en el flujo hacia el norte ocasionan diversos efectos en los organismos marinos, incluyendo la amplitud de distribución del plancton y cambios en las rutas migratorias del salmón.

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INTRODUCTION

The major alongshore currents of the California coast are normally described as an offshore, southward flow—the California Current—and a nearshore, northward flow—the California Countercurrent. Similar coastal currents and countercurrents are found in other eastern boundary current regions such as off the west coasts of South America, northwest Africa, and southwest Africa. The nearshore current flows northward from Baja California throughout the year (Wooster and Reid 1963; Wickham 1975) to Vancouver Island (Ingraham 1967; Reed and Halpern 1976). In fall and winter, the countercurrent is strong and reaches to the surface, inshore of the California Current; the flow is then called the Davidson Current (Hickey 1979). During the summer, persistent northwesterly winds occur along the California coast and blow the surface water southward, covering the countercurrent, which remains as an undercurrent at depths of 200 to 500 m (Chelton 1982). The area influenced by the countercurrent extends up to 500 km offshore from the California coast at depths below 200 m and has been described as the California Undercurrent Domain because of its broad seaward extent under the California Current (Dodimead et al. 1963; Favorite et al. 1976).

This paper describes an index of low-frequency variations of the countercurrent, based on a 10-year time series of frequent hydrographic observations and calculations of dynamic height anomalies at a deep station in Monterey Bay, California. Sea-level, ship-of-opportunity XBT, and surface-drifter data are compared with the index for agreement with the hypothesized variations of flow of the countercurrent. Available biological data are examined for consistency with the flow index.

The fluctuations of the alongshore currents off California are as yet poorly understood but appear to have an important role in changes in distribution and abundance of a variety of marine species. Not only are the changes in currents themselves important in changing the distribution of pelagic organisms, but associated changes in the depth of the density structure may also be significantly related to changes in concentrations of dissolved nutrients and biological productivity. The intensity of upward transport of nutrients from below the thermocline by wind mixing changes markedly with changes in thermocline depth. Bernal (1981) and Chelton (1981) found that long-period variations of zooplankton in the California Current are correlated with fluctuations of temperature in the eastern tropical Pacific. They suggested that zooplankton variations may be related to variations of nutrients advected from the north by the California Current, combined with a reduction of upwelling of nutrients caused by increased thermocline depth. The occurrence off California of organisms of southern origin is also related to increases in water temperature that appear to be associated with increases in the transport of coastal countercurrents (Radovich 1961).

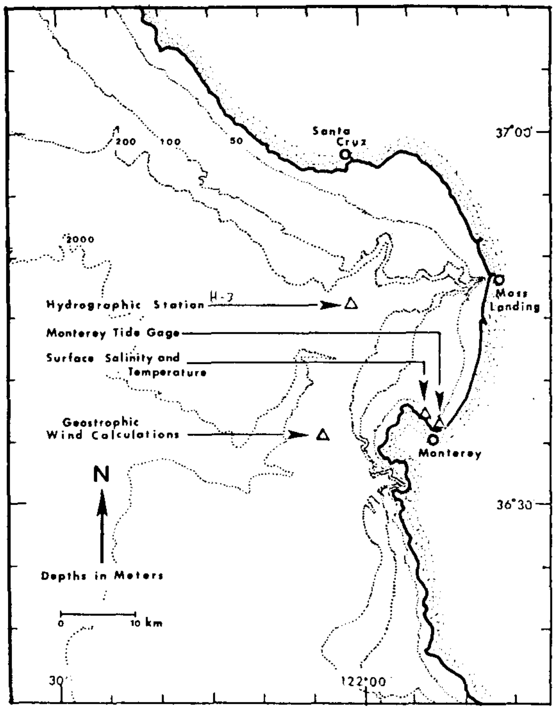

Figure 1. Map of the Monterey Bay, California, region showing location of data sources.

MONTEREY BAY HYDROGRAPHIC DATA

A unique set of time-series hydrographic observations is available in Monterey Bay, about 100 miles south of San Francisco (Bretschneider and McLain 1983). The data were collected at station H-3, located near the mouth of the Monterey submarine canyon, where water depth is more than 900 meters (Figure 1). Hydrographic observations in Monterey Bay were begun in the 1930s by Skogsberg (1936) and continued in the 1950s by Stanford University's Hopkins Marine Station (HMS) as part of the California Cooperative Oceanic Fisheries Investigations (CalCOFI). The sampling program in Monterey Bay was designed to obtain more frequent monitoring of ocean fluctuations than was possible on large-scale CalCOFI surveys (Bolin and Abbott 1963). During the first years of the program, samples were collected at station H-3 to 100 m, but later sampling was limited to the upper 50 m of the water column. In 1968 the sampling depth was increased to over 500 m.[1] HMS sampling at H-3 ceased in December 1973, but sampling was continued at the same location by Moss Landing Marine Laboratories from July 1974 to June 1978 (station 2203).[2] In addition, several expendable bathythermograph (XBT) casts have been taken at nearly the same sampling location to depths of over 400 m by the Naval Postgraduate School, Monterey, California. Salinity values were estimated for each XBT profile so that XBT casts could be used to fill gaps in the time series of hydrographic stations (Bretschneider and McLain 1983). These data were merged to form a time series; 1968 data were deleted because their temperature-salinity curves appeared erratic. The final time series contains 241 hydrographic profiles taken in the 10-year period from 1969 to 1978 and provides good time resolution with nearly biweekly sampling. The data were well distributed seasonally, with 16 to 23 profiles for each month of the year.

Hydrographic data from station H-3 are subject to short-period disturbances associated with internal waves in Monterey canyon (Broenkow and McKain 1972). Errors in the observations of temperature and salinity, local eddies, or other local environmental phenomena probably also contribute short-term noise

[1]Hopkins Marine Station. CalCOFI Hydrographic Data, Collected on approximately biweekly cruises on Monterey Bay, California. Annual Reports for years 1968 to 1973 (mineo.). Hopkins Marine Station, Pacific Grove, California 93950

[2]CalCOFI hydrographic data reports, Monterey Bay, July 1974-June 1978. Tech. Publications 75-1, 76-1, 77-1, 78-1, and 79-1. Moss Landing Marine Lab., Moss Landing, California 95039.

in the data. However, the frequency of sampling to at least 500 m at station H-3 over a multiyear period is unique along the central California coast, and—for ocean monitoring purposes—overrides deficiencies in the data caused by high-frequency noise.

Three distinct seasonal phases of Monterey Bay hydrography were proposed by Skogsberg (1936) and amplified by Bolin and Abbott (1963). These are the upwelling period of summer, a calm warm "oceanic" period in fall, and the Davidson Current period in winter. In January and February, surface water has a high temperature and low salinity (roughly 13°C and 33.2°/oo). As upwelling begins in spring, deep water rises, and the surface water cools and becomes more saline, reaching typical values of 9°C and 34.0°/oo in summer. Warming occurs in the oceanic period in fall, and the surface salinity decreases in winter. At depth (200 to 400 m), conditions are more stable, and the annual temperature-salinity excursions are reduced from their surface values.

The average seasonal pattern of varying oceanographic conditions in Monterey Bay is strongly modified in certain winters by changes in the vertical thermal structure (Figure 2). The 8° and 10°C isotherms were as much as 100 m deeper than their mean depths in winters of 1969-70 and 1972-73, and 20-50 m deeper in the winters 1976-77 and 1977-78. The average depth of the 8°C isotherm lies at depths of 250 and 300 m from August to January, but the 8°C isotherm was at depths of 300-420 m from August to at least November 1969 (deep data in early 1970 are missing) and from July 1972 to February 1973. The 10° and 12°C isotherms were 50-70 m deeper than normal in these two winters, but the anomalous deepenings of these isotherms did not start until October, two months later than that of the 8°C isotherm. The three isotherms were also deeper than normal in the winters of 1976-77 and 1977-78, although not as markedly so as in 1969-70 and 1972-73. Again in these winters, anomalous deepening of the 10° and 12°C isotherms lagged that of the 8°C isotherm. In almost every case, all three isotherms returned to normal depths nearly simultaneously in April or May. Isotherm depths were near normal in the winters of 1970-71, 1971-72, and 1974-75, and were consistently shallower than normal in the winter of 1975-76.

The anomalous deepenings of the deep isotherms may have occurred in two waves, with an initial depression in summer and a second depression the following winter. Anomalous depressions of isotherms were observed in summer 1969 and 1972. Although deep data in the following winters are sparse, second waves of isotherm depression the following winters appear to have occurred. Double depressions were observed in 1976-77 and 1977-78 but were of lesser magnitude than those in 1969-70 and 1972-73.

The anomalous depressions of isotherms were associated with above-normal surface temperatures in late winter. The surface water remained above 12°C until February to April during the winters when the

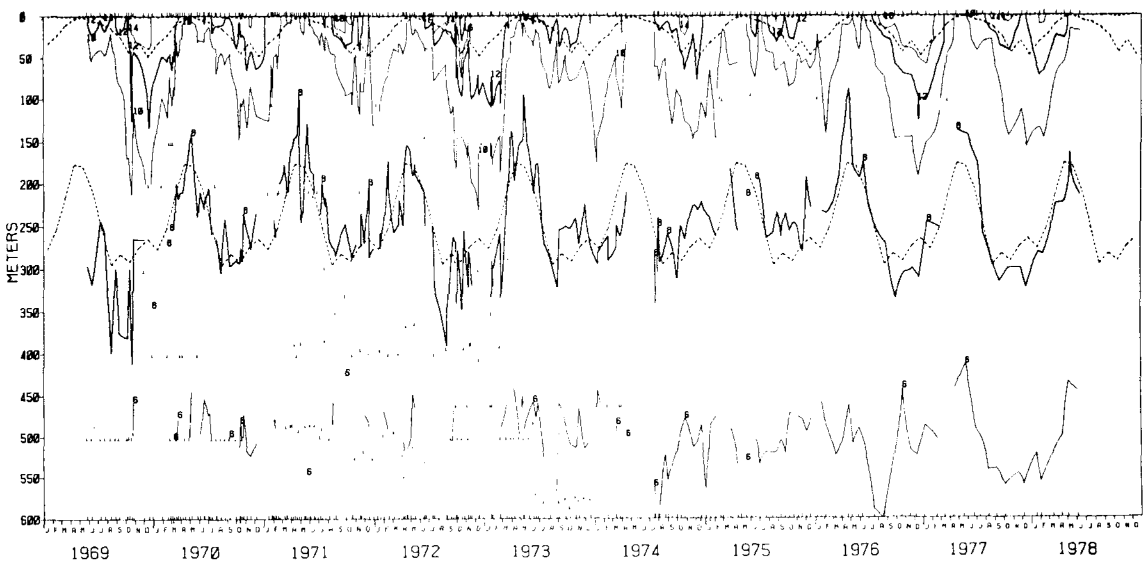

Figure 2. Time series vertical section of temperature (degrees Celsius) at station H-3. Dotted lines show long-term monthly means of 8°, 12°, and 16°C isotherms. Small, inverted "T" marks show greatest depth of data at each hydrographic cast.

8°C isotherm was anomalously deep, but when the 8°C isotherm was near or shallower than normal, the surface water cooled to below 12°C by October or November. (A slight exception to this was in the winter of 1977-78, when the surface water was below 12°C for a short period in November and December 1977 but then again warmed and remained above 12°C until April 1978.)

Salinity at station H-3 (Figure 3) has generally similar interannual variations. Depressions of the 34°/oo isohaline by 200 m or more occurred in late 1969 and in winter 1972-73. Lesser deepenings of 50-100 m occurred in the winters of 1976-77 and 1977-78. The 34°/oo isohaline was at near-normal depths in the winters of 1970-71, 1974-75, and 1975-76, and shallower than normal in winter 1973-74.

Wooster and Jones (1970) described the California Undercurrent as a poleward flow along the coasts of California and Baja California and recognizable by a coastward deepening of isopycnals and poleward transport of warm, saline water. They suggest that the undercurrent can be recognized by the presence of water of greater than about 34.0°/oo on the 150 cl/ton (sigma-t = 26.54) surface. To look for undercurrent water off Monterey, we plotted salinity on constant density surfaces (Figure 4). On the 26.50 sigma-t surface, there were no large increases in salinity during the period of record, and thus pulses of equatorial water were not observed off Monterey. (Isolated anomalously high temperature values of near 10°C occurred in the hydrographic cast data at 300-400-m depths in December 1969 and December 1972. These values are interesting because they occurred at times when unusually high temperatures might have been observed, but they were deleted as erroneous because XBT data from the same months and depths did not show similar high values.)

Low surface salinities were observed at station H-3 in early 1970 and early 1978 (Figure 4), probably as a result of onshore Ekman transport of low salinity offshore water. Chelton (1981) described the low salinities observed on the CalCOFI survey during winter 1977-78 and showed that the low salinity could not have resulted from precipitation alone. Reid et al. (1958) showed a core of low-salinity water (less than 33.0°/oo) on the surface 200-400 km off central California. Saur (1980) showed that, based on surface salinity observations made by ships of opportunity between San Francisco and Honolulu during 1966-74, a core of low-salinity surface water occurs off San Francisco throughout the year and tends to move onshore in spring and offshore in autumn. Onshore transport in winter (Figure 8) could force this low-salinity surface water onto the coast and could have caused the salinity minima observed at station H-3 in February 1970 and March-April 1978. Saur's data on surface salinity also agree well with station H-3 data for 1969-72. Bolin and Abbott (1963) show similar surface salinity minima in Monterey Bay in January 1956 and March 1958, following similar periods of strong onshore transport (Figure 8), although they suggest that the low salinities are primarily due to precipitation. Broenkow and

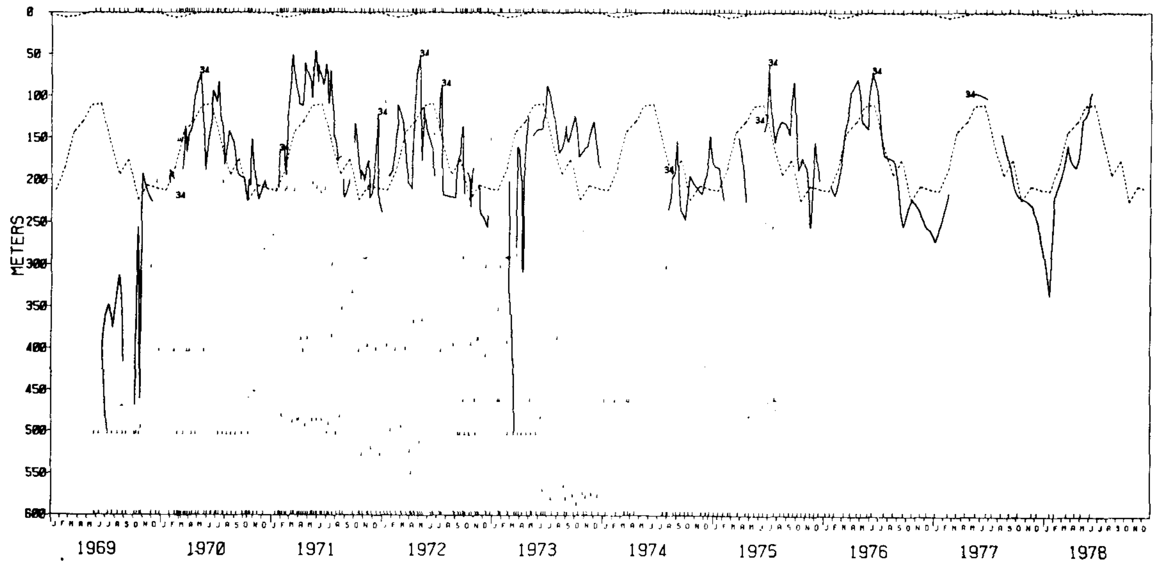

Figure 3. Time series vertical section of salinity (parts per thousand) at station H-3. Dotted lines show long-term monthly means of depth of 33 and 34.00‰ isohaline.

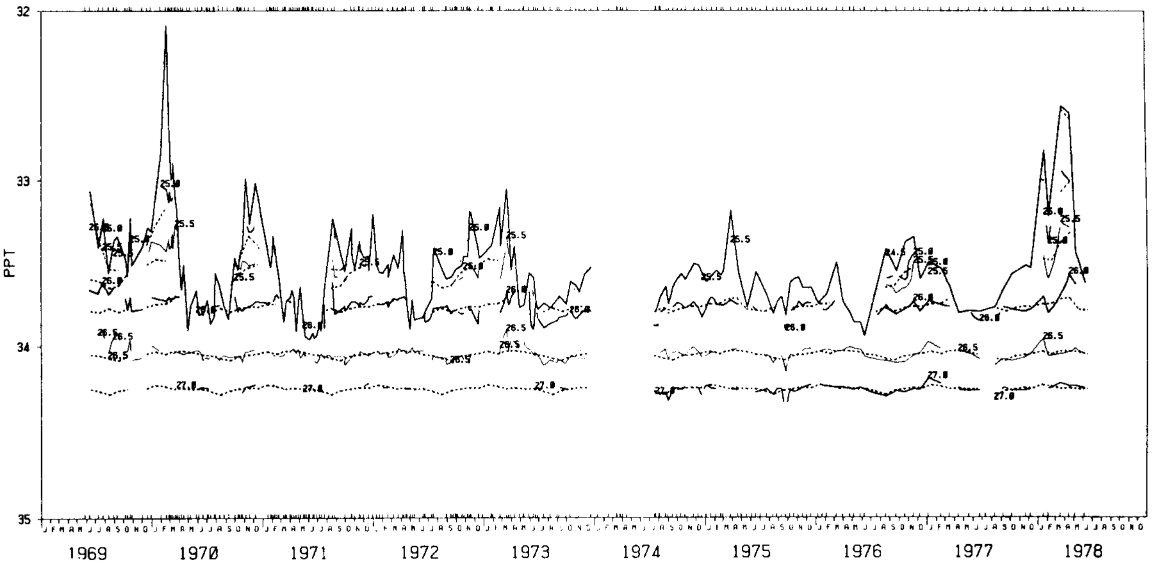

Figure 4. Time series of salinity (parts per thousand) on sigma-t surfaces at station H-3. Dotted lines show long-term monthly means.

Smethie (1978) suggest that lower salinities observed in Monterey Bay in the winter of 1972-73 relative to the winter of 1971-72 were due to more persistent southerly winds in 1972-73 and that the low salinities were associated with storms and consequent heavy rainfall and land runoff.

Dynamic height anomalies were computed for each of the hydrographic profiles at station H-3 and plotted as time series (Figure 5). Although the hydrographic casts generally extended to 500 m or more, we chose 400 m as the reference depth to allow use of the XBT observations. The mean seasonal cycle of 0/400-db dynamic height (shown as dotted lines in Figure 5) had a minimum in May or June and double maxima in

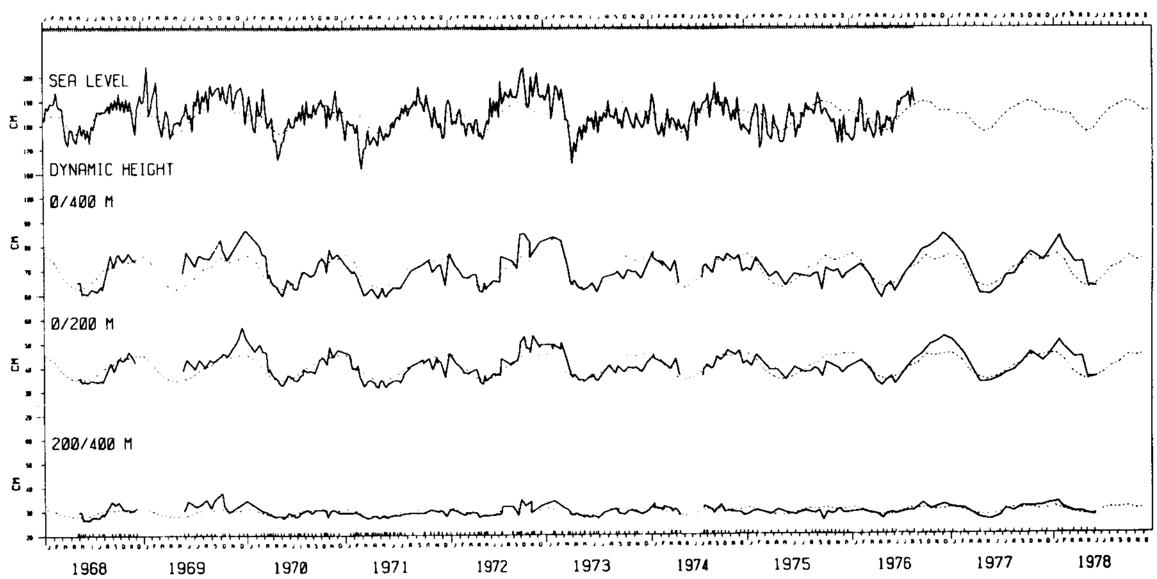

Figure 5. Time series of unadjusted weekly mean sea level (cm) at Monterey, California, and 0/400-db, 0/200-db, and 200/400-db dynamic height (dyn cm) at station H-3. Dotted lines show long-term monthly means.

September and December. The two maxima of the mean seasonal cycle of dynamic height in fall and winter are caused by the double wave of isotherm depressions mentioned previously. Because of the relative greater effect of temperature than salinity in determining density in this region, depression of the thermal structure (and consequent increased dynamic height) overrides the effect of depression of the salinity structure (in reducing dynamic height). Large year-to-year fluctuations occurred in the record of 0/400-db dynamic height with above-normal values of dynamic height in the winters of 1969-70, 1972-73, and to a lesser extent in the winters of 1976-77 and 1977-78. Below-normal values of dynamic height occurred in the winters of 1973-74 and 1975-76.

Most of the fluctuations of the 0/400-db dynamic height were caused by changes in the upper 200 m of water, as is seen by comparing time series of two components of the 0/400-db height; 0/200-db and 200/400-db heights. The 0/200-db dynamic height has a seasonal cycle that is similar to that of the 0/400-db dynamic height with double maxima, in September and December, and a minimum in April. The 0/200-db dynamic height had deviations from its mean seasonal cycle that were similar to the 0/400-db dynamic height deviations: the maxima of the 0/400-db dynamic height in the winters of 1969-70, 1972-73, 1976-77, and 1977-78 are also seen in the 0/200-db series. In contrast to the fairly regular seasonal cycle of the 0/200-db series, the 200/400-db series of dynamic height has little seasonal variation and has minor maxima in the winters of 1969-70 and 1972-73 and a minimum in summer 1977. The maxima in the winters 1969-70 and 1972-73 are associated with the depressions of the thermal structure to depths below 200 m.

Sea level at Monterey had interannual fluctuations similar to the 0/400-db dynamic height (Figure 5). The data plotted are weekly means of hourly sea-level elevations at the Monterey tide gage and were not adjusted for atmospheric pressure fluctuations. The sea-level data show high-frequency fluctuations of 10-20-day period that may be due to pressure changes. Fluctuations of longer period appear to be correlated well between the two series.

The interannual fluctuations of dynamic height at station H-3 and sea level at Monterey are apparently due to large-scale, coast-wide variations in the alongshore currents. If the anomalous depressions of isotherms and related anomalous increases of dynamic height occur primarily near shore, and conditions offshore are more stable from year to year, the anomalous thermal conditions would cause anomalous increases in the slope of the sea surface toward the coast and, hence, anomalous increases in poleward alongshore currents. Thus the time series of dynamic height and related sea-level variations can provide an index of the interannual changes in the flow of the California Countercurrent. Not only can the series of dynamic heights show interyear differences of poleward transport, but on a finer time scale the series may even indicate shorter period changes. The apparent correspondence between dynamic height and sea-level changes on monthly time scales may confirm this.

No long time series of observations of transport of the countercurrent are available for direct comparison with the dynamic height index. The only data on alongshore currents available are from hydrographic surveys, current meters, ships of opportunity, and drifter studies. Many of these data are of short duration and are scattered in time and thus cannot be easily used to resolve interyear differences. We shall examine each of the data sources for comparison with the hypothesized fluctuations of the countercurrent flow, based on the time series of 0-400-db dynamic height from station H-3.

RATIONALE FOR COUNTERCURRENT INDEX

A rationale for a relation between interannual fluctuations of dynamic height at station H-3 and strength of the California Countercurrent can be made based on the data collected on the CalCOFI hydrographic surveys that have been conducted along the coasts of California and Baja California since the early 1950s. Published charts of 0/500-db and 200/500-db dynamic height for particular CalCOFI surveys show that during periods of higher than normal dynamic height at station H-3, intensified poleward flow occurred along the coast.

Direct comparison of time series of CalCOFI and station H-3 data are not possible because the CalCOFI survey data are available much less frequently than station H-3 data. The CalCOFI surveys were not made at regular time intervals but instead were made nearly monthly in some years, quarterly in other years, and not at all in still other years. We compared annual means and seasonal cycles of dynamic height from the two sources. We recognize that different individual years are included in each set of monthly means but neglect the errors introduced. The data for CalCOFI lines 67 and 70 off central California for years 1958-78 were obtained.[3] The data on annual means of dynamic height at station H-3 are based on at least 12 hydrographic casts per month, but annual means of the CalCOFI data are limited by inadequate sampling in certain months, as pointed out by Chelton (1980). For example, there were several months in which no

[3] L. Eber, Southwest Fisheries Center, National Marine Fisheries Service, La Jolla, CA 92037.

observations were available and several others when only one observation was made.

The annual and seasonal ranges of the monthly means are shown in Figure 6. The annual mean dynamic heights on line 70 off Point Sur, south of Monterey, show that the dynamic height normally slopes downward from the coast to a trough 30-40 km offshore (near station 55) and then rises in an offshore direction. By geostrophy, the downward slope from the coast is associated with northward alongshore flow, and the upward slope offshore beyond the trough is associated with southward flow. Chelton (1980) has fit the annual variations of CalCOFI survey data with two harmonics and plotted monthly maps of dynamic height along the California coast. Chelton's maps show a trough off Monterey, parallel to the coast from September to February and located 100-200 km offshore.

The magnitude of the range of annual variations of dynamic height is greatest at the coast and decays in an offshore direction (Figure 6). Since station H-3 is well inshore of the trough and since inshore variability is greater than that in the trough, fluctuations of dynamic height at station H-3 reflect fluctuations of the slope of dynamic height normal to the coast and hence variations of the countercurrent. Huyer (1977) found that off Newport, Oregon, there was a minimum of seasonal variation of steric height about 80 km from the coast.

The trough of dynamic height weakens and moves inshore in summer. This can be seen in monthly distributions of 0/500-db dynamic heights along lines 67, off Monterey Bay, and 70, off Point Sur (Table 1). Nearshore observations are not available from these lines, and thus data from station H-3 are assumed to represent inshore variations along the lines. Mean dynamic height is computed for each station and month, even if only a single observation was available for that location. The number of observations ranges from 1 to 15, with generally greater sampling on line 70 than line 67. (There were 131 observations on line 67, and 211 on line 70.) On lines 67 and 70, the trough of dynamic height (indicated in Table 1 by dynamic heights of less than 80 cm) is generally located near stations 53 or 55 but moves inshore and disappears in June or July. In summer, because of northwesterly winds, alongshore surface wind stress off Monterey is large, with peak values in May or June (Nelson 1977). Wind stress causes upwelling along the coast, and the thermal structure slopes upward toward the coast. The nearshore surface current becomes southerly, weakening the countercurrent and causing the California Current to move inshore and override the countercurrent. These processes cause a redistribution of mass so that the trough of dynamic height moves inshore and disappears in summer.

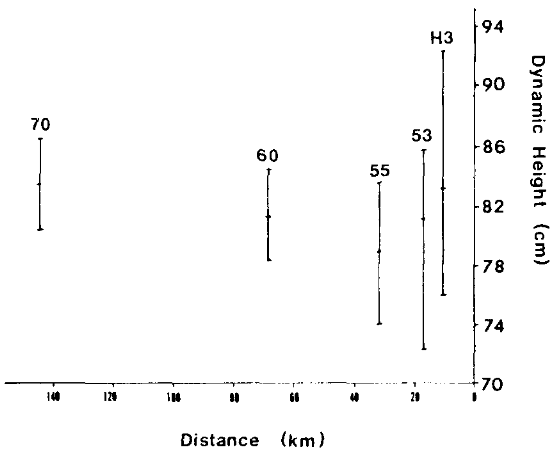

Figure 6. Annual means and seasonal ranges of 0/500-db dynamic height (dyn cm) at station H-3 and along CalCOFI line 70.

An index of countercurrent transport can be made by calculating the difference of dynamic height at station H-3 and the trough minimum. This difference (Table 1) is greatest from October to February, with peak values in December, suggesting that maximum countercurrent flow occurs in December. This is in agreement with plots of Hickey (1979), which show strongest northward alongshore flow from November to January.

COMPARISON WITH TIME SERIES SEA-LEVEL DATA

Reid and Mantyla (1976) have shown that in the North Pacific south of about 40°N, monthly mean sea levels are typically highest in late summer and early fall and lowest in winter as a consequence of the annual heating and cooling cycle. North of about 40°N, however, the seasonal cycle shifts phase, and sea levels are highest in winter and lowest in summer. This phase shift cannot be explained by seasonal heating and cooling. Reid and Mantyla showed that the high sea levels of winter are instead a consequence of the circulation of the subarctic cyclonic gyre of the North Pacific Ocean. The California Countercurrent can be considered a southern arm of the cyclonic gyre along the California coast. The countercurrent has strongest flows in winter, causing sea level to slope upward toward the coast and accounting for the phase shift south of 40°N. Sturges (1974) accounted for high sea levels and dynamic heights near Neah Bay, Washington, in terms of stronger northward along-

TABLE 1
Monthly Mean 0/500-db Dynamic Height (cm) at Station H-3 and at Stations on CalCOFI Lines 67, off Monterey Bay, and 70, off Point Sur

CalCOFI line 67

	Months											
	J	F	M	A	M	J	J	A	S	O	N	D
H-3	87	87	81	77	76	77	79	84	85	89	85	92
53	82	—	79	—	—	—	—	84	—	—	—	—
55	84	84	84	79	78	77	79	80	82	82	88	83
60	82	85	83	83	80	81	78	81	82	84	—	82
70	—	78	—	—	76	76	84	85	79	82	96	—
Difference (H-3-trough)	5	—	2	—	—	—	—	4	3	7	—	10

CalCOFI line 70

	J	F	M	A	M	J	J	A	S	O	N	D
H-3	87	87	81	77	76	77	79	84	85	89	85	92
53	86	82	80	80	78	72	79	80	84	85	—	86
55	79	80	76	74	77	79	84	77	—	81	83	—
60	82	80	84	80	78	81	82	82	80	81	84	82
70	83	80	84	85	86	83	84	83	82	84	81	85
Difference (H-3-trough)	8	7	5	3	−1	5	—	7	5	8	2	10

Tables are contoured, and dotted line indicates trough of dynamic height. Difference of monthly mean dynamic height at H-3 and trough is also shown.

shore currents in winter. Similarly, Marthaler (1976) compared monthly mean sea level at Newport, Oregon, with currents observed with current meters on the continental shelf off Newport during 43 different months. He found that sea level and alongshore currents were strongly correlated, with best correlations from November to May or June when northward flows were strongest.

Sea level at Monterey is closely correlated with dynamic height at station H-3 for the years of common record (Figure 5; Bretschneider and McLain 1983). Sea level at other stations along the West Coast from Los Angeles to Neah Bay, Washington, (Figure 7) had similar year-to-year variability in the dynamic height at station H-3. Periods of above-normal sea level generally occurred in the latter portions of certain years: 1951, 1957, 1958, 1963, 1965, 1969, 1972, 1976, and 1977. Below-normal sea levels occurred in 1948, 1949, 1955, 1956, 1973, and 1975. Because of the similarity of sea level and dynamic height in years when both data series are available, sea level can also be used as an index of alongshore currents off central California (Chelton 1981). This relation allows inexpensive monitoring of alongshore currents from shore stations on an interannual time scale rather than by expensive ship surveys.

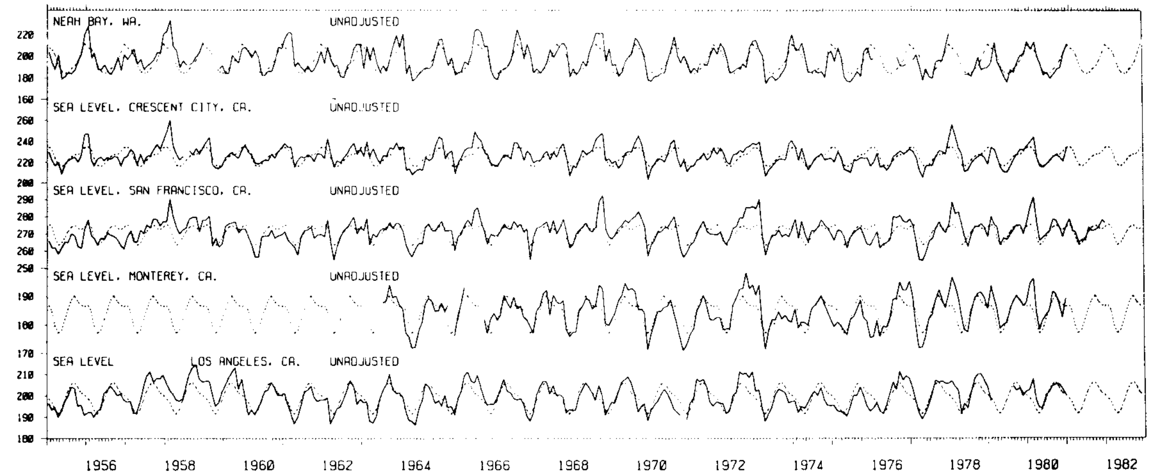

Figure 7. Time series of sea level (cm) at selected West Coast tide gage stations. Data have not been adjusted for atmospheric pressure effects. Dotted lines show long-term monthly means.

COMPARISON WITH SHIPS-OF-OPPORTUNITY XBT DATA

Approximately biweekly sections of sea-surface temperature, salinity, and subsurface temperature have been made since 1966 by expendable bathythermograph (XBT) from ships of opportunity on the route from San Francisco to Honolulu (Saur et al. 1979). The XBT drops were made at approximately 120-km intervals along the route, with sections repeated at approximately 2-week intervals. Price (1981) has computed dynamic heights from these XBT data and has computed an index of strength of the countercurrent. Price used climatological hydrographic data to compute long-term mean temperature-salinity relationships and thus to estimate salinity from observed temperature data. This method of monitoring ocean currents has the advantages of relatively low cost (compared to repeated hydrographic observations from research vessels) and good time resolution but suffers from limited depth range and possible inaccuracies in the estimation of salinity. The XBT drop closest to the coast was often 100 km or more offshore, and thus the observations may have often missed the countercurrent. In spite of the problems, Price's index of the flow of the countercurrent (called V4) shows fair agreement with estimates of countercurrent flow from station H-3 dynamic height data and with sea-level data at both Monterey and San Francisco. All series show high values in late 1969 and in late 1972-early 1973, and low values in 1968, 1970, late 1973, and 1974. Price's index shows a very strong double peak in 1972-73; this may be related to the double waves of isotherm depression seen at station H-3.

COMPARISON WITH HYDROGRAPHIC AND DRIFTER DATA

The available hydrographic and sea-level data indicate significant interannual fluctuations of alongshore currents. The periods of strong flow are discussed below and compared to available hydrographic survey and surface drifter observations.

1957-59

High sea levels (Figure 7) were observed from 1957-59, suggesting a period of anomalously strong northward alongshore currents. Reports presented at the Rancho Santa Fe Symposium in 1958 described numerous unusual oceanographic and biological events observed in 1957 and 1958; these were attributed to anomalous northward coastal flow. Schwartzlose (1963) noted very strong northward transport of drift bottles along the coast in 1958. Tully et al. (1960) described anomalous increases in water temperature off British Columbia in 1957 and 1958.

1969-70

The computed dynamic height values from station H-3 were above normal in July and August 1969, peaked in December, and declined to relatively low values by May 1970. Schwartzlose and Reid (1972) considered that the Davidson Current was well developed in November 1969. Drift bottle recoveries indicated that coastal water was flowing northward from southern California at a minimum speed of 13 km/day. Recovery records for CalCOFI drift bottle studies (Crowe and Schwartzlose 1972) showed considerable northward flow in both October and November 1969 from central California. Several drifters released off central California during these months were recovered in southeastern Alaska, and numerous recoveries came from Oregon and Washington. The magnitude of northerly flow noted during these months was comparable to that observed during November 1957 and January 1958.

1972-73

Wickham (1975) made hydrographic and drogue surveys off Monterey in early August of 1972 and 1973. His data show that water between the surface and 500 m was warmer, more saline, and had a greater northward velocity during August 1972 than August 1973. Water in August 1972 appeared to have "southern" characteristics similar to water observed by Molnar (1972) inshore of a transition zone south of Point Arguello during June 1972. Water offshore of this transition zone had "northern" characteristics similar to water found off Monterey in June. Wickham (1975) further suggested that water observed near Monterey in August 1972 was southern water advected northward from the region of Point Arguello at a speed of at least 5 cm/sec. This is in agreement with the station H-3 data, which show that an intrusion of relatively warm water into Monterey Bay began sometime in June or July 1972 (Figures 3 and 5).

Additional evidence of intensification of the countercurrent in June-July 1972 appears in the hydrographic and current studies of Broenkow and Smethie (1978). Based on hydrographic data from station H-3 between 1971 and 1973, they concluded that local upwelling events, evidenced by a shallowing of near-surface isotherms, generally corresponded to peaks in local northerly winds. They noted an exception to this relationship in July 1972, however, when a temperature maximum occurred despite the presence of northerly winds.

In a surface study, Blaskovich (1973) released drift cards monthly in Monterey Bay between September 1971 and April 1973. He found southward flow from March to May1972, but from June to September 1972 most recoveries were made on the eastern shore of Monterey Bay, indicating a lack of typical summer southward flow. In another drifter study conducted in the Monterey Bay area between November 1971 and April 1973, Griggs (1974) found a good correlation between southward surface drift and northerly winds from March to May 1972. The relationship broke down in June, July, and September 1972, when drifter recoveries demonstrated substantial northward surface flow despite the presence of northerly winds.

Evidence that the intensification of the countercurrent in 1972 was not confined to central California waters can be found in the results of a drift-bottle study conducted from early March to early August 1972 off northern Oregon (Rothlisberg 1975). Northward surface drift persisted from March to mid-April. Currents in late April were transitional, with a large southerly component, and recoveries in May indicate that southward flow had become dominant. In spite of strong northerly winds from May through August, however, a reversal to northward flow was indicated by recoveries from June and July releases.

Broenkow and Smethie (1978) concluded from the station H-3 hydrographic data that northward flow in the winter of 1972-73 was stronger than that of the previous winter. This result was also shown by drifter releases during the winters of 1971-72 and 1972-73, which indicated northward flow in both winters but long-distance drifts only during winter 1972-73. Blaskovich (1973) reported the recovery of a drift card in Oregon that was released in October 1972 at Monterey, as well as an Oregon recovery and a Washington recovery from November 1972 releases. Paradoxically, another card released in October 1972 found its way south to San Simeon, a distance of 150 km. Griggs (1974) does not give detailed accounts of individual drifter movements, but recoveries during December 1972 and February 1973 indicated that a more extensive northward flow occurred during this period than from November 1971 to February 1972. Griggs, like Blaskovich, found both long-distance southern and northern movement during October 1972.

1976-77

Anomalously high dynamic heights at station H-3 in 1976-77 would indicate that intensification of northward alongshore flow may have started in June 1976 and reached its maximum influence by the end of December. Comparative data are unavailable off central California, but Tsuchiya (1980) summarized the results of nine nearshore cruises off southern California from 1974-77. Tsuchiya found that during October 1976 to January 1977, the water in the upper 300 m was warmer and more saline than normal. He related the change to a large-scale warming of the eastern North Pacific, but an intensification of northward flow along the coast at the time may also have been a cause.

A decline of dynamic height values to lower than normal occurred in summer 1977, suggesting a period of stronger than normal southward flow. The dynamic height data indicate that an intensification of the countercurrent began in fall 1977 and apparently peaked in

January 1978 (one month later than in the previous winter) before declining to minimum values in May 1978. A cooperative United States-Poland oceanographic survey was conducted along the west coast of the United States during August and September 1977 (Ingraham and Love 1978). Geostrophic currents derived from the survey data indicate that surface flow was generally southward all along the coast, but flow at 150 m (computed relative to 500 db) was generally northward except in the vicinity of the Columbia River. Ingraham and Love considered these observations to be evidence that a substantial northward flow existed at depth during late summer 1977 over the outer continental shelf and slope. Gardner (1982) found evidence of Pacific equatorial water on the continental shelf north of Vancouver Island in April and November 1977, with greater amounts in November.

CAUSES OF COUNTERCURRENT FLUCTUATIONS

Several processes act in concert to drive alongshore currents. Hickey (1979) has described the countercurrent in terms of wind stress and the curl of the wind stress. Wind stress seems the more important. Several studies off Oregon (e.g., Cutchin and Smith 1973; Huyer et al. 1978) have shown that currents over the continental shelf observed with moored current meters are highly correlated with sea level at nearby tide gages and that both respond rapidly to changes in forcing by alongshore winds.

Sharp drops of both dynamic height at station H-3 and sea level at Monterey occurred in early 1970, 1973, and other years. This suggests that the transition between northward and southward flow in spring may be rapid. Huyer et al. (1979) describe sharp flow reversals off Oregon during March of both 1973 and 1975. They refer to these current reversals as a "spring transition" and suggest that such reversals occur each spring and represent a relatively permanent change from winter (northward flow) to summer (southward flow) conditions on the shelf. The time series of dynamic height at station H-3 (Figure 5) suggests that such pronounced reversals do not occur every year and may be weak or oscillatory, as in 1971, 1974, and 1975. Spring reversals following winters of above (below)-normal sea level and dynamic height tend to be more (less) intense than normal.

Whereas the mean seasonal cycle of dynamic height at station H-3 suggests that southward flow occurs during the first half of the year and northward flow during the second half of the year, reversals of the direction of flow are common within both periods. These can be seen as sharp reversals of dynamic height at station H-3 and can be explained by assuming that on large space scales, water to the north of H-3 is colder than that to the south. Northward flow (or anomalously weak southward flow) would then cause increased water temperature (averaged over the upper 400 m) and consequently, increased dynamic height (assuming also that salinity effects are small). Conversely, southward flow (or anomalously weak northward flow) would cause decreased water temperatures and dynamic heights. Thus reversals of the time slope of dynamic height at coastal locations such as station H-3 can reflect reversals of coastal flow.

Evidence that fluctuations in the dynamic height reasonably depict actual current reversals is available from drifter movements in 1972. The dynamic height data suggest that a sharp reversal in currents occurred between mid-September and mid-November 1972. The implied strong northward flow followed by strong southward flow is substantiated by the long-distance transport of drifters, both to the north and south, reported to have occurred in October 1972 by Blaskovitch (1973) and Greggs (1974).

Sverdrup transport set up by curl of the wind stress over the region is a second process driving the countercurrent but is less well understood than wind stress itself. Nelson (1977) has computed and plotted monthly maps of wind stress curl off the West Coast based on historical ships' wind observations. Nelson's maps show fine seasonal detail (about 110-km resolution) but because of scarcity of historical data, they do not show interyear variations. Chelton (1980) computed similar maps of wind stress curl, based on analyzed fields of surface pressure, which can be computed monthly but have lower spatial resolution (about 300-km resolution) than Nelson's maps and are subject to poor resolution of surface pressure gradients along coasts because of coastal mountains (Bakun 1973). Both Nelson's and Chelton's maps show general negative wind stress curl offshore and a band of positive curl along the coast, a situation that would produce poleward alongshore currents.

Nelson's maps show several peaks of positive wind stress curl along the coast: 42°N south of Cape Blanco, 38°N near Point Reyes, 34°N south of Point Conception, 31°N off northern Baja California, and 27°N south of Punta Eugenia. Chelton's maps show only one of these areas—the major feature south of Point Conception. To examine the effect of Sverdrup transport on alongshore currents, we computed time series of monthly wind stress curl at these locations along the coast for the years 1946-80 from monthly mean surface pressure fields developed by FNOC and using methods of Bakun (1973, 1975). The time series of wind stress curl did not appear to be correlated with the dynamic height series and hypothesized alongshore currents. This result is similar to that of Hickey (1979), who found little correlation of alongshore currents with wind stress curl, and with Bretschneider and McLain (1983) who found no correlation of Sverdrup transport with dynamic height at station H-3. Wind stress curl may, however, contribute a long-term net tendency for poleward alongshore currents because of the long time periods required for spin-up of a curl-driven current (Chelton 1982).

In addition to wind stress and wind stress curl, a third process that drives alongshore currents is local forcing by the component of Ekman transport toward the coast and resultant depression of the isotherms near the coast. Cairns and Lafond (1966) described short-period fluctuations in shallow water off San Diego, caused by onshore Ekman transport. The process seems of greater importance on longer time and space scales. Southerly winds and resulting onshore transport are relatively infrequent off California but become increasingly common in winter with distance to the north so that onshore transport and downwelling occur each winter along the coasts of the Pacific Northwest and the Gulf of Alaska (Bakun 1973). Figure 8 shows the time series of the component of Ekman transport normal to the coast, again computed by the methods of Bakun. Off California at latitudes 36°N and 39°N, there were anomalously strong onshore Ekman transports during the winters of 1957-58, 1960-61, 1969-70, 1972-73, 1977-78, and 1979-80. Anomalously strong onshore transport would cause anomalous depression of the thermal structure and consequently cause anomalously high sea level and dynamic height along the coast. Northward flow would result from upward slope of the sea surface toward the coast. Thomson (1972) proposed onshore Ekman transport as an explanation for annual variations in the northward penetration of relatively warm water off the British Columbia coast during 1955-56. Douglas and Wickett (1978) explained above-normal bottom-water temperatures on the continental shelf off Vancouver Island in February-March 1978 as a result of anomalously strong onshore Ekman transport.

A fourth process that drives alongshore currents on interannual time scales is remote forcing by propagation of a depression of the thermocline polewards along the coast from the Eastern Tropical Pacific. McCreary (1976) and Hurlburt et al. (1976) modelled the effect of a weakening of the trade winds over the equatorial Pacific and a resultant depression of the thermocline along the coast of Peru. They showed that the depression would be propagated both to the north and south along the coast as a coastally trapped Kelvin wave. Associated with the wave are poleward coastal jets formed by quasi-geostrophic adjustment to the depressed pycnocline along the coast. Enfield (1981) reviewed the available literature on this process, and Mysak et al. (1982) looked for effects of baroclinic waves in physical and biological time series data along the coast.

A major realization of this process occurred in 1972 when a strong El Niño occurred off Peru, and warm water intruded into the area and depressed the thermocline. Wyrtki (1975) presented monthly maps of the topography of the 15°C isotherm surface off Peru, and Enfield (1981) presented temperature sections off Ecuador and Peru during the event. Their data show

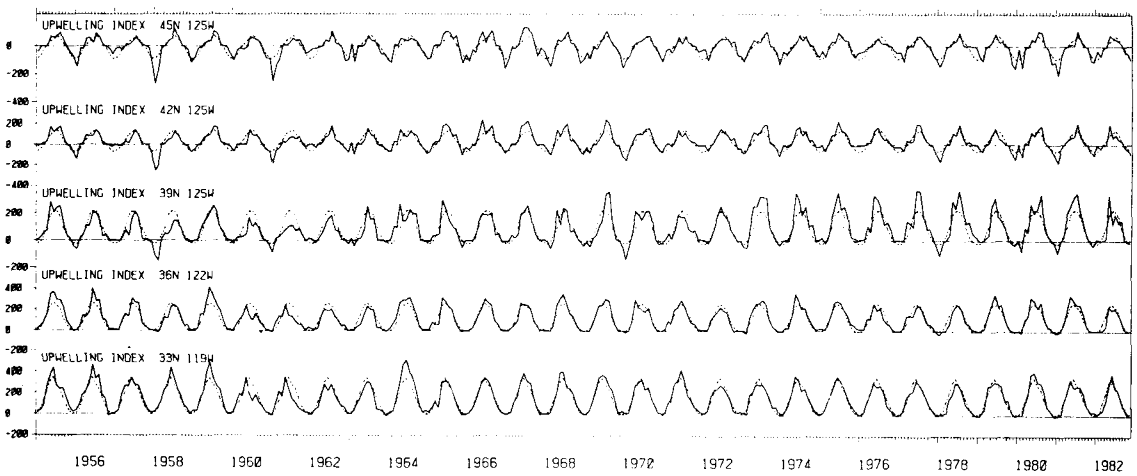

Figure 8. Time series of component of Ekman transport normal to the coast (m^3/sec/100 m of coastline) at selected locations along the West Coast. Data computed by methods of Bakun (1973, 1975). Dotted lines show long-term monthly means.

that the 15°C isotherm is often within 20 m of the surface, or surfaces off the Peruvian coast with coastal temperatures less than 15°C. During the 1972 event, however, the 15°C isotherm was depressed along the coast to depths of 20-100 m in February-March, 60-120 m in August-September, and 150-250 m by December.

The anomalous depression of the thermal structure was observed to propagate both to the north and south. Wyrtki (1975) described changes observed to the south in the depth of the 26.4 sigma-t surface off northern Chile during the 1972 event. During normal years, this surface is between 50 and 100 m along the Chilean coast and deepens to 150-200 m at about 300 km offshore. During June to August 1972, the surface was depressed to depths of 200-300 m all along the coast of northern Chile. It was deepest near the coast and rose to depths of less than 150 m about 200 km offshore, implying a poleward alongshore current.

The propagation of the wave northward from the equator is poorly documented because of lack of hydrographic observations during late 1972 off North America. The waves enter the Gulf of California and dominate conditions there (Baumgartner et al. 1979). High-frequency waves (of 10-30-day period) may be trapped by the Gulf of California and not continue up the Pacific coast of Baja California (Enfield 1981). The data series off Monterey suggests that waves of lower frequency continued up the coast and caused maximum depression of the thermocline in Monterey Bay in December 1972.

The propagating wave can be seen in monthly mean sea-level data. Bretschneider and McLain (1979) showed that sea level at stations from Chile to Alaska had coherent fluctuations at low frequencies over long stretches of coast. These fluctuations were apparently associated with El Niño phenomena in the Eastern Tropical Pacific. Enfield and Allen (1980) explained the coherence by poleward-propagating coastally trapped Kelvin waves. Bretschneider and McLain (1983) presented time-distance isogram plots of anomaly of monthly mean sea level at stations along the coast from Peru to Alaska for 1963 to 1974. Their figures show that in January 1972, a period of anomalously high sea level developed off Peru and persisted throughout the year. The region of anomalously high sea level expanded northwards and reached California by July or August 1972. A second, stronger pulse reached San Francisco in October to December 1972. These waves were apparently related to the double wave of isotherm depression observed at that time at station H-3. Enfield (1981) explained the double waves of isotherm depression and associated peaks of high sea level off Peru as oceanic events related to relaxation of winds over the mid-Pacific, subsequent recovery, and on successive reflections of Kelvin and Rossby waves off the eastern and western ocean boundaries.

The four processes—wind stress, Sverdrup transport, onshore Ekman transport, and propagation of disturbances from the tropics—do not act in unison but have independent effects that may act in different combinations each year. Many of the years of high sea level and dynamic off-California height were years of El Niño events in the Eastern Tropical Pacific (e.g., 1958, 1963, 1972, and 1976) while others (e.g., 1957-58, 1960-61, 1969-70, 1972-73, 1977-78, and 1979-80) had winters of local onshore transport (Figure 8). Years such as 1973 and 1975 had normal or below-normal values of both dynamic height and sea level and were years in which neither El Niño nor anomalously strong Ekman onshore transport occurred. In 1976, there was an El Niño in the Eastern Tropical Pacific that apparently created a coastal Kelvin wave, which caused the observed depression of the isotherms at station H-3 and the hypothesized increased countercurrent flow the winter of 1976-77. In contrast, in 1977 there were normal conditions in the tropics, but strong onshore Ekman transport at 36°N in December 1977 and January 1978 apparently caused the depression of isotherms at station H-3 the winter of 1977-78. In some years, such as 1958 and 1972, both processes occurred and reinforced one another.

The characteristic time scales of these processes differ, and thus it may be possible to distinguish between them. Onshore Ekman transport is related to atmospheric fluctuations and persists only one or two months, whereas the effects of propagating coastal waves persist for several months or longer. Evidence for this is seen in 1976 when the peak of dynamic height was long-lasting and probably related to a propagating coastal wave. In 1977, when onshore transport apparently caused the anomalously high dynamic height, the peak lasted only a month or so.

The timing of the peaks of dynamic height may give clues to the processes causing them. Hickey (1979) suggested that the speed of the undercurrent has two seasonal maxima, one in summer and the second in winter, but she cannot easily relate the maxima to variations of wind stress and wind stress curl. Alternately, the double maxima of speed of the undercurrent may result from (1) the double maxima of isotherm depression in years of strong coastal wave propagation, (2) a combination of a summer peak caused by coastal propagating waves and a winter peak caused by onshore Ekman transport, or (3) some combination of these processes.

Hickey (1979) also suggested that the intensity of the summer maximum of the undercurrent increases toward the south, whereas the winter maximum decreases toward the south. She could not, however, explain these relations from distributions of wind stress and wind stress curl. These relations would be consistent with an explanation of the summer maximum related to poleward-propagating coastal waves (which originate to the south) and the winter maximum related to onshore Ekman transport (which is a local process along the coast).

EFFECTS OF THE COUNTERCURRENT ON MARINE ORGANISMS

Fluctuations in strength of the countercurrent have had notable effects on the distribution and abundance of various marine organisms. Many of these effects are poorly understood and documented, but available observations of unusual distributions of organisms do agree fairly well with the hypothesized fluctuations of the countercurrent. Only a few examples can be given here, and much research remains to be done on these effects. Radovich (1961) described many such unusual occurrences during the "warm-water" years 1957-59 and earlier, particularly in 1926, 1931, and 1941. He recognized that some of the occurrences were more closely associated with changes in the flow of the countercurrent than with increases in water temperature.

Phytoplankton

Bolin and Abbott (1963) described fluctuations of the countercurrent and associated phytoplankton catches off central California for the years 1954 to 1960, and Abbott and Albee (1967) updated the series for 1961 to 1966. Garrison (1979) provided additional data for the years 1976 and 1977. All the authors found significant year-to-year variations, with plankton organisms characteristic of low latitudes more prominent in the warm years. They suggested the importance of advection effects in causing the changes. Also, a general northward extension of subtropical and tropical phytoplankton during the warm years was noted by Balech (1960).

Zooplankton

Blackburn (1979) described fluctuations in the distribution of the salp *Doliolum denticulatum* off California during 1969. He noted that the earlier work of Berner and Reid (1961) had shown that the distribution of *Doliolum* was unusual in 1957 and 1958 in that some *Doliolum* remained inshore off southern California during the winter of 1957-58, whereas in 1949-55, they had not. Blackburn also noted that the distributions in 1969 were more similar to those in 1957-58 than to those in 1949-55. This supports the conclusion that both 1957-58 and 1969 were years with strong northward intrusions of southern water. Other species of invertebrates that have well-documented northern extensions of their range during warm-water years are the sand crab, *Emerita analoga*, (Efford 1970) and two euphausiids, *Euphausia eximia* and *Nyctiphanes simplex* (Brinton 1960).

Hubbard and Pearcy (1971) studied the distribution of salps in plankton collections off Oregon in the years 1961-64. They found that during these years several salps of probable southern origin, particularly *Thalia democratica*, occurred only in late 1963. This was a period of slightly higher than normal sea level and, although no dynamic height data are available from station H-3, probably stronger-than-normal countercurrent.

Gardner (1982) observed the occurrence of several subtropical zooplankton species in samples taken along the British Columbia coast in April and November 1977. He noted more widespread occurrence of the subtropical forms in November than April and associated their occurrence with a warm-water intrusion.

During 1978, salps were observed in large numbers off British Columbia and southeastern Alaska and were associated with other unusual observations (Lasker 1978; McLain and Ingraham 1980). As has been mentioned, onshore transport the previous winter caused intensified northward flow in 1978 and may explain these observations.

Pelagic Red Crab

Pelagic red crab, *Pleuroncodes planipes*, are normally found off the central and southern coast of Baja California (Mais 1974). The range of the species extended north as far as Monterey during the warm period from mid-1957 to early 1960 (Berner 1960; Glynn 1961; Longhurst 1967). Longhurst examined CalCOFI data from 1955-60 and distinguished two periods (1955-57 and 1958-60) with dissimilar latitudinal distributions of red crab. A northward extension of their range began in June and July 1957 in the area between Point San Eugenia and Cape Colnett, Baja California. By October 1957, crab were found near Ensenada, and in December they appeared off San Diego. In 1958 the main population probably moved no farther than San Diego, but isolated groups may have moved as far north as Monterey. In late 1958, northward movement began again, and by early 1959, crab were widely distributed north to San Pedro. Massive strandings occurred at San Pedro in 1959; by early 1960, the northward extension seemed to have ceased. Glynn (1961) reported massive strandings of red crab at Monterey in January 1960. CalCOFI data indicate that a general retreat of the northward range extension began in January 1960 (Longhurst 1967). By the end of 1961 the northern limit and center of abundance had shifted southward to about the same latitude as in mid-1957. Longhurst concluded that some factor other than temperature was responsible for this unusual northward movement. He believed that some alteration in circulation allowed crab to be swept north by coastal countercurrents.

Subsequent to the warm years (1957-60), red crab were found on Monterey beaches in the winters of 1969-70 and 1972-73 (Hardwick and Spratt 1979). The appearance of red crab north of their usual range in these winters had also been observed on Fisheries Resources Sea Surveys of the California Department of Fish and Game. The following observations were extracted from reports of those surveys.

Sea surveys to assess biomass of northern anchovy, *Engraulis mordax*, were conducted several times a year off southern California and Baja California from 1964-78. In 1979 and 1980, the number of surveys was reduced. On the surveys in November-December 1969, red crab were found consistently north of their usual range—as far north as La Jolla, California. By February 1970, crab were absent from northern Baja California and southern California waters. Because red crab were found on Monterey beaches during this period, some crabs must have moved through southern California waters undetected.

The Fisheries Resources Sea Surveys reported that large quantities of red crab were again found off Los Angeles in February 1973. "Quantities far exceeded previous observations including the warm-water years of 1957-58." Red crab maintained a presence off southern California through August 1973. By October 1973 their occurrence was unusual, a few still being found near San Diego.

Unusual observations were made in January 1977 when crab were found north to Cape Colnett, Baja California. Red crab appeared again a little farther north at Ensenada in January-February 1978. In February 1979 no unusual observations were noted, but by April 1979 the Sea Surveys reported the "most extensive influx of this species since 1973 occurred. They were taken on 10 scattered stations from San Diego to Santa Cruz Island." In February 1980, crabs were found from Point Dume southward.

In many of these studies, the organisms were not only found north of their usual range, but those on the northern edges of the range extensions were found inhabiting water cooler than where they are normally found. Because of this, theories developed to explain this extension involve northward forcing by the coastal countercurrents rather than southern populations simply expanding into favorable environmental conditions.

Sockeye Salmon

Adult sockeye salmon normally return to the Fraser River by rounding the south end of Vancouver Island via the Strait of Juan de Fuca; fewer than 20% of the run return around the north end of Vancouver Island via Queen Charlotte Sound. Royal and Tully (1961) reported that in 1958, however, the fish returned in large numbers around the north end of the island, causing reduced availability to fishermen in the Strait of Juan de Fuca. Tully et al. (1960) suggested that the northward shift was associated with anomalous oceanographic conditions during 1957 and 1958. Wickett (1977) listed peak fractions of fish returning around the north end of Vancouver Island as 35% in 1958, 24% in 1966, 25% in 1967, 34% in 1972, and 22% in 1974. Blackbourn[4] provided more recent values of 56% in 1978, 33% in 1979, 70% in 1980, and 69% in 1981. The very anomalous and persistent northward displacements of sockeye migration routes in recent years correlate roughly with onshore Ekman transport off northern California (39°N in Figure 8) the previous winter and may be related to flow of the countercurrent.

CONCLUSIONS

Fluctuations of dynamic height computed from frequent hydrographic data at station H-3 in Monterey Bay during 1969-78 agree well with sea-level data at Monterey on interannual and even monthly time scales.

A trough of dynamic height exists some 20-40 km off the coast in winter and weakens and moves inshore in summer. Interannual variations of dynamic height in the trough are of smaller magnitude than the variations at station H-3 and thus to a first approximation, fluctuations of the slope of dynamic height normal to the coast can be approximated by the fluctuations of dynamic height at the coast. Thus the interannual fluctuations of dynamic height and sea level at the coast can be used as an index of alongshore currents. By geostrophy, increased (decreased) dynamic height and sea level are associated with anomalously strong (weak or even reversed) northward flow.

The cause of the interannual variations of dynamic height and sea level appear to be due to two major processes: (1) remote forcing by poleward-propagating coastal trapped waves from the tropics

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that depress the thermal structure along the coast in some years by 50-100 m, and (2) local forcing by anomalous onshore Ekman transport in winter. Both processes are accompanied by coastal jets, which appear as anomalously strong alongshore currents. Interannual fluctuations of wind stress are certainly important in forcing alongshore currents, but fluctuations of wind stress curl do not appear related to interannual changes of coastal sea level nor of dynamic height at station H-3.

Interannual fluctuations of the countercurrent appear to affect many different organisms, including phytoplankton, zooplankton, and sockeye salmon. Many of the effects are only poorly documented and understood and thus deserve further investigation.

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