ANNUAL VARIABILITY OF OCEAN CURRENTS AT 350-M DEPTH OVER THE CONTINENTAL SLOPE OFF POINT SUR, CALIFORNIA

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ABSTRACT

Currents were measured at 350 m from May 1989 through February 1995 over the 800-m isobath off Point Sur, California. Mean flows were directed toward 334°T at 7.6 cm/s. The pattern of monthly mean flow reveals a distinct annual pattern: the spring transition begins in mid-April and is marked by a tripling of undercurrent speeds, onshore flow, and minimum temperatures. The strong poleward flow persists until mid-July and is accompanied by steady warming. When the flow decelerates, temperatures remain elevated until mid-December, when cooling begins.

El Niño conditions resulted in warming during much of the period between July 1991 and November 1992; no dramatic change of the current pattern was observed.

INTRODUCTION

Several recent attempts have been made to use CalCOFI data to resolve the annual cycle of currents along the central California coast. Chelton (1984) and Lynn and Simpson (1987) used 23 years of CalCOFI hydrographic data to examine the variability of geostrophic velocity relative to 500 db over the outer continental slope off Point Sur. They found poleward deep flow over the slope from June through February, with a maximum in December (about 3 cm/s at 350 m). At depth, weak equatorward flow occurred from March to May (> -2.5 cm/s).

Relatively few current measurements have been made over the slope off central California (Wickham et al. 1987; Chelton et al. 1988; Huyer et al. 1989), and these measurements show the annual cycle to be different than that inferred from geostrophy: poleward flow appears to occur in spring and summer, and is 3–5 times greater than that obtained from hydrographic data. Compared to the hydrographic measurements, the current meter data span only a short period of time (6 months–2 years), and the data reported by Wickham et al. (1987) have many gaps.

In order to better understand both the annual variability and the changes in the currents that occur during El Niño events, we began a program of current measurements over the upper slope near Point Sur, California, in 1989. Although there is considerable year-to-year variability in the observed currents at Point Sur, the six years of data that have been obtained for 350 m reveal a consistent pattern of annual variability, which is described below. This annual pattern will also be used to classify and discuss the observed interannual variability of the flow.

OBSERVATIONS

Since May 1989, the Naval Postgraduate School has maintained a current meter on the continental slope due west of Point Sur, California, at 36°20'2"N, 122°10'2"W, where water depth is 800 m, roughly halfway between CalCOFI stations 67.55 and 70.53, and about 24 km from the coast. Currents, temperature, and pressure were measured with Aanderaa RCM8 vector-averaging current meters. Because of instrument failures, there is a relatively continuous record only at middepth. Unfortunately, two gaps exist in this time series, from February 7 to April 20, 1993, and from November 23, 1993, to February 9, 1994, when the mooring was cut by trawlers.

Table 1 describes the current meter installations used in the present study. The observation depth was close to 350 m, except for the seventh mooring (April 1, 1992, to April 19, 1993), when currents were observed at 260 m. To estimate the effect of the depth difference, we examined the vertical shear at the mooring site; this had been measured with acoustically tracked dropsondes on 34 occasions between April 1989 and April 1991. The mean shear and standard deviation, 260 m–350 m, was -1.0 ± 2.4 cm/s for the east component of velocity, 1.6

TABLE 1
Mid-depth Current Observations at 36°20'2"N, 122°10'2"W

Setting no.	Start date	End date	Meter depth
1	5/12/89	8/26/89	365
2	8/26/89	12/13/89	387
3	12/16/89	4/27/90	350
4	5/15/90	10/8/90	352
5	10/11/90	5/11/91	346
6	5/16/91	4/27/92	353
7	4/30/92	4/19/93	260
8	4/22/93	11/23/93	355
9	2/9/94	2/11/95	350

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± 1.9 cm/s for the north component. Given the uncertainty and small difference, we used the 260-m current data without adjustment. From 19 CTD casts at the mooring location, the temperature difference and the standard deviation of the temperature difference between 260 m and 350 m were 0.76°C ± 0.14°C. The temperature gradient was nearly the same at both depths—0.0084°C/m at 260 m and 0.0082°C/m at 350 m. So we adjusted the 260-m temperature data by simply subtracting 0.76°C.

The Aanderaa current meters acquired hourly data. A ducted paddlewheel is used to measure speed, and a vane to measure direction. Paddlewheel counts are converted to speed, and every 1.2 minutes the speed and direction are converted to north and east velocity components, which are in turn summed over the one-hour sampling period. The speed measurement is accurate to ±1 cm/s for speeds between 2 cm/s and 50 cm/s (the rotor stalls at speeds less than 2 cm/s, and accuracy is 2% of speed when speed is greater than 50 cm/s). The accuracy (precision) of direction is ±3 degrees (0.35 degrees). Temperature and pressure are sampled once per hour with an accuracy (precision) of ±0.05°C (±0.025°C) and ±4 db (±0.4 db), respectively. Compass, temperature, and pressure calibrations are done before and after deployment. Hourly data were filtered to remove tides by means of a cosine-Lanczos filter with a width of 121 hours and a half-power point of 46.6 hours. The resulting time series was decimated to four samples per day and was further subsampled for various plots.

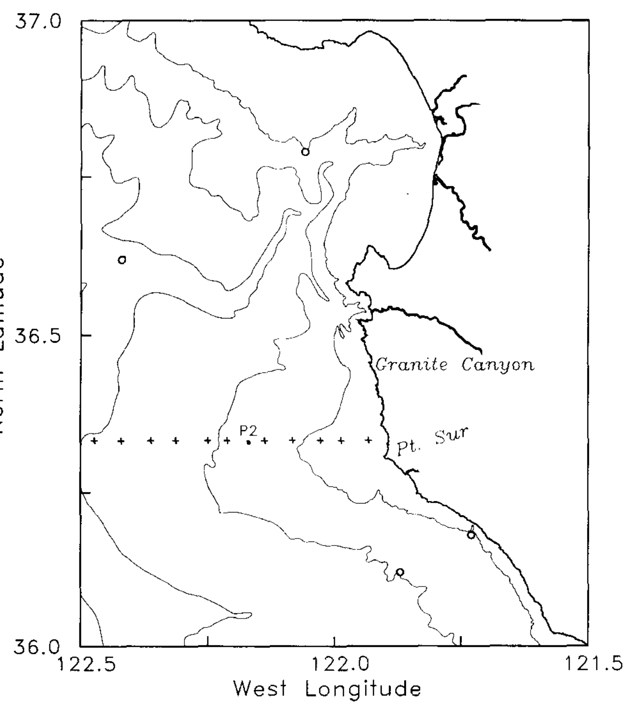

Figure 1. Position of the current meter mooring (P2) off Point Sur, California. Open circles (○) indicate the position, from north to south, of CalCOFI stations 67.50, 67.55, 70.51, and 70.53 (these stations were last occupied in October 1984). Crosses (+) indicate the location of POST hydrographic stations (Tisch et al., 1992). 200-m, 1,000-m, 2,000-m, and 3,000-m isobaths are shown.

Figure 1 shows the mooring location, bathymetry, coastline, nearby CalCOFI hydrographic stations, and stations used by Tisch et al. (1992). The bathymetry to the south reflects the general trend of the California coastline; the Monterey Submarine Canyon modifies the bathymetry to the north. This causes the isobaths near the mooring to tend north-south in contrast to the NNW orientation of the coast. During the upwelling season from mid-March through September, a wedge of cold, upwelled water is found off Point Sur, and offshore-flowing jets of cold water are occasionally observed in AVHRR imagery during July–September (Breaker and Mooers 1986).

RESULTS

Mean Conditions

Figure 2 is the scatter diagram formed by the end points of daily current vectors. The elliptical shape is due to the constraint the coast imposes upon across-shore flow, but differs from those typical of shelf regions (figure 7 in Huyer 1990) in the scattering of points to the southwest because of currents that flow offshore. The mean current was directed toward 334°T at 7.6 cm/s. The principal mode for the speed histogram was 4 cm/s, and the maximum speed was 44.1 cm/s. The principal

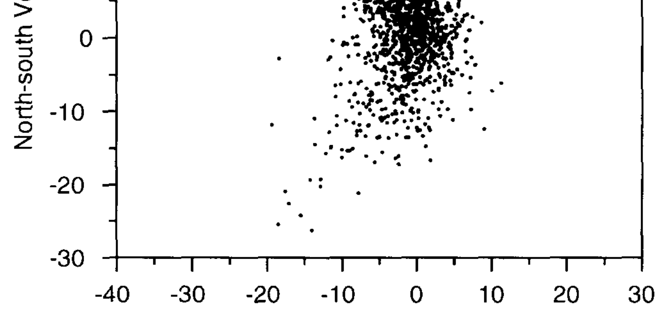

Figure 2. Scatterplot of daily 350-m current observations, May 12, 1989, to February 11, 1995. Dots have been placed at the heads of the vectors representing the currents.

mode for the direction histogram was 338°T, and the principal axis was directed toward 345°T. The direction of the mean flow partakes of the trend of the isobaths upstream of the flow for both poleward and equatorward flow. For poleward flow, this creates a local divergence to the north of Point Sur because the local topography is oriented north–south. This divergence may contribute to anticyclonic flow observed off Monterey Bay (Tisch et al. 1992).

The integral time scales[2] for flow along the major and minor axes were 18 and 8 days, respectively. Standard deviations were 9.7 cm/s and 4.1 cm/s for the major and minor axes. The maximum and minimum for the alongshore (onshore) flow were 43.6 and −21.8 (15.0 and −25.6). Equatorward flow was observed only 22% of the time.

The mean temperature was 7.18°C, and its standard deviation was 0.31°C. The integral time scale for temperature was greater than that obtained for either velocity component—26 days. The maximum temperature—8.14°—occurred on August 9 (year-day 222), 1992, and the minimum temperature—6.26°—occurred on May 1 (year-day 122), 1994.

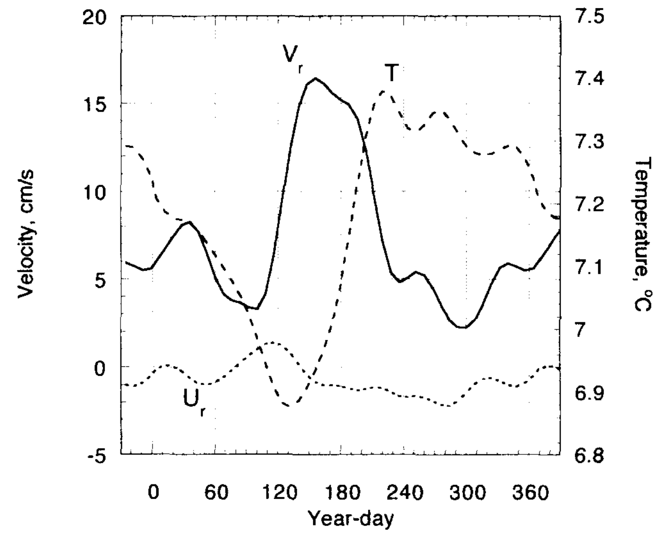

Figure 3. Annual variability of currents and temperature at 350-m depth. Alongshore currents (V_r) are represented by the *solid line*, across-shore (U_r) currents by the *dotted line*, and temperature (T) by the *dashed line*. Data have been averaged for all years in successive 8-day blocks, then smoothed again to represent monthly averages. To clarify the seasonal variability that occurs at the beginning and end of the year, the time has been extended so that 20 days of December data are plotted to the left of January 1, and 20 days of January data are plotted to the right of December 31.

Annual Variability

We constructed an average annual cycle by first collecting the data into calendar years, then averaging across all years in 8-day blocks. No attempt was made to synthesize missing data; the divisor for averaging was simply reduced accordingly when gaps were included. These data were in turn smoothed by a filter with a half-power point at 32 days, resulting in a series of "monthly averages" with 8-day temporal resolution (figure 3).

The alongshore component of velocity (directed toward 345°T) was dominated by a strong pulse in poleward flow that occurred between April 17 (year-day 108) and August 23 (year-day 236). The poleward flow accelerated from 3 cm/s to 16 cm/s between April 9 and May 27 (year-days 100 to 148) and remained greater than 14 cm/s through July 14 (year-day 196). The poleward flow decreased to 5 cm/s on August 23 (year-day 236), and remained at about 5 cm/s for the rest of the year. Before the onset of this large pulse in poleward flow, a smaller pulse of poleward flow occurred on February 5 (year-day 36). The onshore component of velocity was positive (flow toward the coast) at the start of the poleward pulse, but became offshore when the poleward flow reached 16 cm/s. The strength of the offshore flow increased slowly to −2 cm/s on September 27 (year-day 271), thence relaxing to −1 cm/s by November 3 (year-day 308).

Almost all the temperature variability occurred in the first 200 days of the year. Beginning on December 5 (year-day 340) of the previous year, the temperature decreased from 7.29°C to the minimum, 6.87°, on May 11 (year-day 132). This occurrence of a temperature minimum agrees with the mid-May occurrence of maximum density at 350 m at CalCOFI station 70.53 (figure 18 in Lynn and Simpson 1987), which is located southeast of our mooring (figure 1). The temperature minimum occurred one month after the start of the poleward pulse and at the end of the associated onshore flow. Temperature then increased, reaching a maximum of 7.37°C on August 7 (year-day 220). Between August 7 (year-day 220) and December 21 (year-day 356), the temperature remained high, between 7.3° and 7.2°.

Although the monthly average middepth flow over the upper continental slope off Point Sur was poleward all year, the flow had a clear annual character. The poleward acceleration of flow in April, which begins with onshore flow and minimum temperature, marks the beginning of the transition to summer conditions. The acceleration of poleward flow is accompanied by a steady increase in temperature. When the poleward flow decreases in early August, neither the temperature nor the offshore flow changes character. Poleward flow reaches a minimum in early October, and temperatures begin to cool in December. It is unclear which of these latter events represents a fall transition.

[2]The integral time scale is a correlation time scale and a measure of the period of the process that dominates a given time series. Observations separated by a period of time equal to the integral time scale can be assumed to be independent for statistical purposes.

The relationship between alongshore flow and temperature is complex. Geostrophic adjustment to an increase in poleward flow would cause isopycnals (isotherms) to deepen toward the coast, resulting in a temperature increase at a fixed depth on a mooring. Temperature increases could also be caused by a regional deepening of the pycnocline (thermocline), which involves no change in the alongshore flow. Finally, for a given stratification, advection of equatorial water from the south could increase the temperature (and salinity) on a density surface. Our single current meter and mooring cannot distinguish between these. Evidence that some of the observed warming is associated with advection of equatorial waters has been provided by Lynn and Simpson (plate 2, 1987), who show the seasonal characteristics of σ_t = 26.6 along CalCOFI line 70. At station 70.53, the minimum temperature (about 7.7°C) and shallowest depth (about 210 m) of σ_t = 26.6 occurred in May, warmest temperatures (>8°C) in October, and deepest depth (>260 m) in December and January. This suggests that geostrophic adjustment is responsible for the initial spring warming but that subsequent warm temperatures were associated with advected (equatorial) waters.

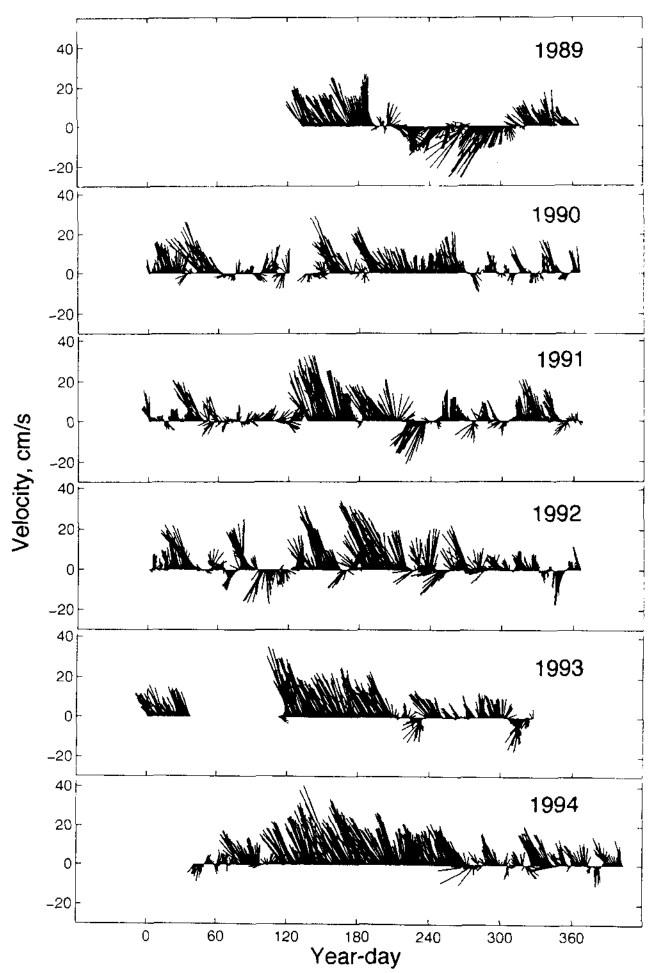

Figure 4. Time series of currents at 350-m depth. Data have been detided with a cosine-Lanczos filter with 121 hourly weights and a half-power point of 46.6 hours. Two vectors are plotted each day.

Interannual Variability

The pattern of annual variability described above provides a canonical description of the flow, which can be used to contrast year-to-year variability. Daily currents and temperatures are shown for the period 1989–94 in figures 4 and 5. In discussing these figures, we will call the strong poleward flow that occurs in the spring and summer the "spring jet," in contrast to shorter-period "poleward pulses" that occur in other months. Short-period events when the alongshore flow is equatorward and the onshore flow is less than −10 cm/s will be referred to as "squirts."

1989. The observations began on May 12, 1989, well after the spring transition. The poleward velocity pulse ended in mid-July (year-day 197), and the temperature maximum occurred shortly thereafter. This was followed by what turned out to be the most anomalous flow of the entire record, a 100-day period of equatorward offshore flow, including three squirts that occurred fortnightly beginning on September 1 (year-day 245).

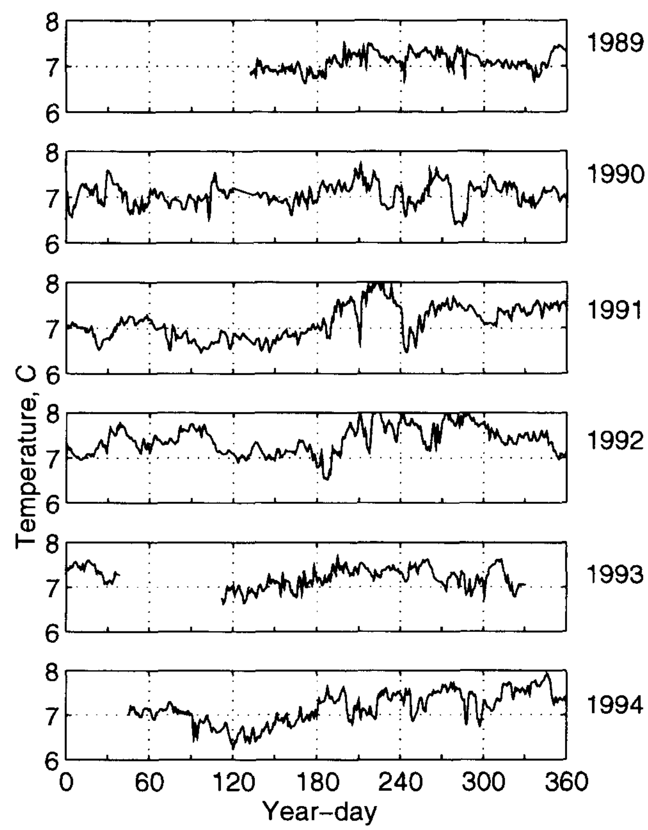

Figure 5. Time series of temperature observations at 350-m depth. Data have been detided with a cosine-Lanczos filter with 121 hourly weights and a half-power point of 46.6 hours. Two data points are plotted each day.

1990. Pulses of poleward flow occurred in January and late February. A strong onshore pulse occurred on April 10 (year-day 100), but the spring jet did not develop until June 1 (year-day 153) and persisted through the summer months until September 26 (year-day 270). The spring jet was accompanied by warming from 6.9° to 7.6°. The coldest temperature, 6.4°, occurred on October 6 (year-day 280), just after a short pulse of equatorward and onshore flow, but the temperature quickly recovered.

1991. After a short pulse of poleward flow in mid-February, the temperature cooled steadily from late February to early April. The temperature minimum, 6.5°, occurred on April 7 (year-day 98), and two weeks later the spring jet began, accompanied by onshore flow. The spring jet extended through July 28 (year-day 210), and warming continued through August 11 (year-day 224), which marked the warmest temperature, 8.0°. A squirt occurred in mid-August (year-day 230).

1992. This was an El Niño year, anomalous both because of the warm winter temperatures and the lack of a period of sustained onshore flow accompanied by equatorward or weak poleward flow during the winter. During winter the poleward flow was maintained by pulses in mid-January to mid-February and again in late March. The spring jet began on April 29 (year-day 120) and lasted until September 6 (year-day 250), although the spring jet was interrupted by equatorward and onshore flow on June 19 (year-day 171; the strongest onshore flow observed during our record). The temperature minimum, 6.5°, occurred 17 days after this onshore event. The temperature rapidly recovered, and the warmest temperature recorded during the entire record, 8.1°, was observed on August 9 (year-day 222). In late September (year-day 270), cooling began and continued through February 1993. Squirts were observed in early April (year-day 100) and in early September (year-day 250).

1993. An instrument failure occurred on February 6, and the mooring was not cycled until April 22. Data recorded on April 22 show equatorward flow, which—coupled with the observed minimum temperature, 6.6°, on April 23 and onshore flow—led us to believe that this was the beginning of the spring jet. The spring jet continued through July 23 (year-day 205), accompanied by steady warming. In mid-August (year-day 230) and early November (year-day 315), squirts occurred. Between September 21 and October 21 (year-days 265 and 295), temperature cooled by about 0.5°, but the warmest temperature of the year, 7.6°, was observed on November 6 (year-day 311). The mooring was cut by a fishing boat on Thanksgiving Day, drifted northward, and was retrieved due west of Moss Landing the following week.

1994. The mooring was reset on February 9. A poleward pulse of amplitude 18 cm/s was observed on March 25 (year-day 85), but the spring jet began on April 19 (year-day 110) and extended through September 26 (year-day 270). The temperature minimum, 6.3°, occurred on April 20 (year-day 120), and the ocean steadily warmed at 350 m through July 7 (year-day 189) to 7.6°. Flow was onshore at the start of the spring jet, and a squirt was observed in early October (year-day 280). Poleward pulses occurred in late October and late November (year-days 295 and 335), and the warmest temperature of the year, 7.9°, was observed on December 12 (year-day 347).

DISCUSSION

Subseasonal Variability

Two features of shorter period appeared in our records—poleward pulses and offshore squirts. Vertical arrays (Wickham et al. 1987; Tisch 1992) show these features to be vertically coherent throughout the water column. Yet coherence with moorings on the shelf (Chelton et al. 1988) and 25 km seaward (Tisch 1992) is low, perhaps due to the short Rossby radius, 15 km (Tisch 1992). The poleward pulses resemble Kelvin waves seen in equatorial current meter records, and Wickham et al. (1987) speculate that these features are Kelvin waves. An onshore-offshore array of current meters and pressure gauges across the upper slope is needed to definitively describe the physical character of these features.

Chelton et al. (1988) note that Point Sur appeared to be a southern boundary of a region of convergence in 1984, with poleward flow and surface waters of equatorial origin to the south, and equatorward and offshore flow and fresher surface waters to the north. Their 70-m current record shows no offshore flow. Satellite images and laboratory studies show that offshore flow of cold, upwelled waters frequently occurs at Point Sur, and the 350-m record at P2 suggests that these flows can penetrate the thermocline. Our data suggest that this occurs most frequently in the fall, after the spring jet ends.

Relationship to Granite Canyon Surface Observations

In order to see how the annual cycle at 350 m compares with surface conditions, we constructed an annual cycle of sea-surface salinity and temperature observed at Granite Canyon (figure 6). The Granite Canyon data consist of daily observations for the period 1989–94, filtered in the same manner as daily detided mooring data. During winter, sea-surface salinity at Granite Canyon was $S \approx 33.5$; during March and April, there was a transition to summer conditions. During this transition, salinity increased to $S > 33.8$ (as a result of coastal upwelling); the rate of cooling increased; and minimum temperatures (10.7°C) occurred at the beginning of May—the

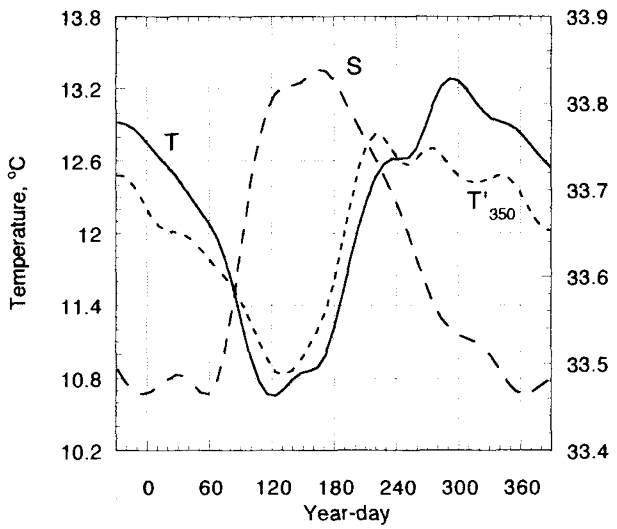

Figure 6. Annual variability of sea-surface temperature (T) and sea-surface salinity (S) at Granite Canyon, 1989–94 (the location of Granite Canyon is shown in figure 1). Data have been processed in the same manner as those shown in figure 3. The annual 350-m temperature (T'_{350}) cycle (figure 3) has been increased and amplified to ease comparison with surface data.

same time that temperature minimums were observed at 350 m.

High salts and low temperatures persisted during May and June at Granite Canyon. Beginning in July, surface waters steadily freshened and warmed. The temperatures reach a maximum of 13.3° in late October, in contrast to the 350-m temperatures, which reach a maximum in August.

Despite the fact that different processes act at the sea surface, it is clear that the spring transition from winter to summer conditions is closely linked at the surface and at middepth over the upper slope. The timing of the onset of this transition is marked by increasing salinities at the surface and by increasing poleward velocities at middepth, the latter lagging the former by 40 days. Although the spring transition has been observed to occur over a few days (Lentz 1987), especially off northern California and Oregon (Strub et al. 1987), the transition may not be as rapid along central California (Strub et al. 1987). Breaker and Mooers (1986) note that a rapid drop in temperature occurred at Granite Canyon in only 6 of the 13 years that they studied.

Annual Variability

Although at the start of this paper it was noted that previous current measurements failed to define an annual cycle (Wickham et al. 1987; Chelton et al. 1988; Huyer et al. 1989), the results of those measurements fit well with the annual cycle documented here. In 1979 and 1980, measurements were made over the continental slope just south of Point Sur at 35°9'N (Wickham et al. 1987). The annual variation that they observed included a spring transition followed by maximum poleward flow in May–June, with velocities exceeding 15 cm/s. Their observations, which spanned the period from January 10 to March 3, 1979, indicated a transition from eastward to northward flow in mid-February. In 1980, the spring transition was marked in mid-March by a southward flow, which rotated counterclockwise, becoming eastward and then poleward in late March. This period was marked by a decrease in temperature from 7.6° to 6.9°.

The measurements of Huyer et al. (1989) include the period April 1981 to August 1982 and were obtained in water 400 m deep over the upper slope at 38°5'N. At 350 m, the mean direction (338°T) was the same as observed at 350 m at Point Sur, but the mean speed (4.2) and variability (standard deviation, 7.5 cm/s) were less than observed at Point Sur. In 1982, Huyer et al. (1989) observed a spring jet in April and May, following a period of onshore flow. Sustained poleward flow also was observed in July 1981 and July–August, 1982.

Chelton et al. (1988) report on current measurements at a much shallower depth, 70 m, over the upper slope off Point Sur for the period March 1–August 1, 1984. Their data show a pulse of poleward flow in early March followed by equatorward flow in mid-March and April. The "spring jet" appears to begin on May 9 (year-day 130). Chelton et al. (1988) also note the disagreement between measured flow and that estimated from geostrophic shear.

Tisch et al. (1992) computed geostrophic currents relative to 1,000 m; these show occasional substantial flow at 500 m, to the degree that use of a 500-m reference results in an apparent surface flow of the opposite sign. It is also clear from our measurements that disagreement between measured and geostrophic flow arises because of the existence of barotropic flow over the upper slope at Point Sur.

The annual cycle appears well defined, especially the variability associated with the spring transition. In response to increased southward wind stress (see figure 7 in Chelton 1984), the thermocline tilts upward toward the coast, accelerating the southward flow of the California Current and simultaneously lowering the temperature at a given depth next to the coast. The southward wind stress also increases the poleward-directed alongshore pressure gradient force at the coast. This eventually accelerates the undercurrent. This, in turn, results in warming at depth, first due to a deepening of isotherms associated with geostrophic adjustment to the poleward flow, and later due to advection of warm (salty) equatorial water. When the undercurrent decelerates, the warm water remains in the area.

It is more difficult to explain deceleration of the spring jet, the timing of the start of winter cooling, and the role of the onshore pulse. Chelton (1984) shows that the local wind stress curl near Point Sur is about 0.02 N m^{-2}/100 km from December through June, and then doubles in July, just as the southward wind stress begins to relax. The 350-m cooling begins as the wind stress curl decreases, and perhaps onshore flow of offshore (subarctic) waters contributes to the observed cooling.

El Niño

The principal source of interannual variability in California's coastal waters is associated with El Niño, and the principal physical manifestation of this interannual variability is subsurface warming next to the coast (Cole and McLain 1989). With respect to the 1992 El Niño, our observations show that waters were anomalously warm during most of the period from July 1991 to November 1992, and the temperature minimum usually associated with the spring transition was not observed in 1992. A comparison of smoothed, monthly mean data (not shown) for this period with the annual cycle shown in figure 3 yields anomalies of as much as 0.5°C.

Given the large year-to-year variability of the velocity field, it is more difficult to identify anomalous velocity behavior associated with this warming. Sustained bursts of poleward flow occurred in November 1991 and January 1992, and onshore flow was almost zero during the winter of 1992. The current meter records of 1992 were also characterized by strong reversals of flow in winter and spring; such reversals were not observed in other years.

Value of Long Time Series

An annual signal has been derived; it would have been ambiguous if there were only a year or two of data available. The currents for any given year or pair of years may be very noisy, dominated by shorter-period events that have much greater energy than the mean flow. For example, Tisch (1992) reasonably concluded after examining the first 17 months of this data set that the data were dominated by a 215-day signal and that no canonical pattern existed to explain temporal means. Once an annual pattern becomes recognizable, it is possible to see changes that occur from year to year, to determine long-term trends, and to quantify interannual variability.

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