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# Observations of the California countercurrent

by J. B. Wickham[1]

## ABSTRACT

Spatially dense observations in consecutive years in a region within about 50 km of the continental shelf show a complex structure of southern water undergoing dilution by mixing as it flows northward. An eddy a few tens of km in diameter appears to be a major contributor to the mixing process. Marked differences are seen in structure and flow between the two years.

## 1. Introduction

In recent times eastern boundary currents have received increasing attention, owing largely to interest in upwelling, a characteristic feature of such regions with important implications for fisheries and related economic matters. Another characteristic feature of such regions is a poleward countercurrent of what is called "southern water" (in the Northern hemisphere) with anomalously high temperature and salinity. The countercurrent is usually narrow compared to the equatorward flow and inshore of it. Where this flow is submerged, as it may be, it is called an "undercurrent". The countercurrents are of interest because of the role they play in the dynamics of the boundary currents and for their influence on activities, such as fishing (El Niño being a dramatic example) and sound ranging, as well as on coastal marine climate and small-scale near shore circulations for which they may be an important driving mechanism.

One prerequisite for understanding the role of the current in any of these matters is that its structure and its time variations be adequately described. Wooster and Jones (1970) review the known features of the California Current system and add specifics from their studies of the flow and structure off Baja California of the undercurrent. They conclude by suggesting experiments aimed at providing answers to a number of questions still outstanding about the countercurrent. These include:

(1) The mapping of the northward extent of the high salinity water.
(2) Monitoring of the southern water flow in order to define its temporal variations.
(3) Detailed observation of the current structure to facilitate understanding of the mixing processes.

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[1] Department of Oceanography, Naval Postgraduate School, Monterey, California, 93940, U.S.A.

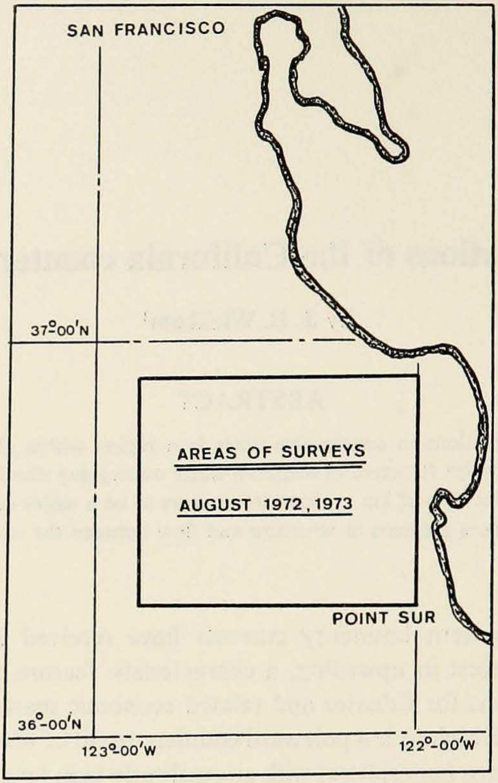

Figure 1. Region of high-density surveys of upper 500 meters.

(4) Comparison of geostrophic currents with independent measures of current in order to test the utility of geostrophy to describe flow in areas of such complexity.

In addition there is a basic need to describe on a fine scale this complex boundary region so that adequate sampling procedures can be adopted for future monitoring programs and to provide data bases for statistical descriptions of these complex areas. These matters are central to the present study.

The region to be examined in detail here lies within a rectangular parallelopiped which is located, as shown in Fig. 1, just west of the continental shelf off Monterey, California. It extends from the surface to depth 500 m, northward about 55 km from 36°20′N, and westward about km from 122°W. The fundamental need is taken to be a detailed description of the structure and flow in that volume. In particular, observations are made on a horizontal grid much finer than is traditionally used in hydrographic surveys in order to permit horizontal definition of very narrow streams of southern water, and continuous profilers provide high-density vertical sampling. Station plans are shown in Fig. 2 for the two principal surveys on which

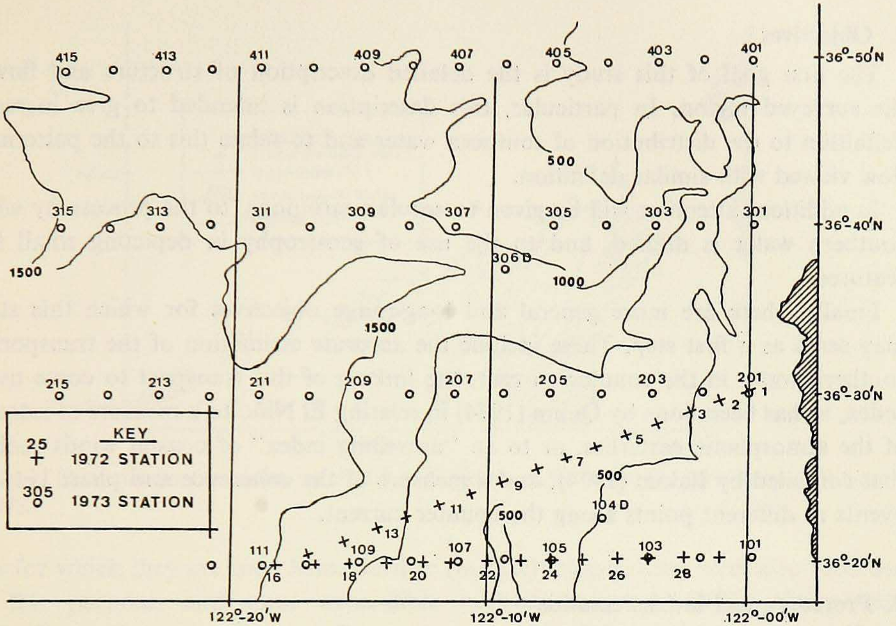

Figure 2. Station locations for cruises of 1972 (1–29) and 1973 (101–415) and topography (depths in fathoms).

this study is based, one in August of 1972 and another a year later. The maximum spacing of stations in a direction normal to the coast is about 5 km.

In both cruises 1972 and 1973 drogues were followed beyond the range of the salinity and temperature observations into the northern part of the region studied (see Figs. 7 and 8). Such observations using a continuous profiler (STD) had been planned for those regions, but electrical trouble developed in the conducting cable making further use of the STD impossible. In 1972 a number of expendible bathythermograph (XBT) drops was taken in the vicinity of the drogues to fill in the temperature field (positions are shown in Fig. 12), and in 1973 also the line of stations 401–415 was observed with XBT soundings.

Many of the observed features of eastern boundary flows are illustrated in dynamical models having simple wind fields as the driving forces. The two-layer steady-state model of Yoshida (1967) shows a poleward flowing undercurrent, and the multi-layer model of McNider and O'Brien (1973) has an equatorward jet at the surface. A time-varying wind is a feature of a model developed by Thompson and O'Brien (1973); this shows multiple bands of upwelling and downwelling with corresponding alternations of the horizontal flow. These features are all present, or at least there are strong indications of them, in the data on which this study is based. Since details of the actual wind field are poorly known, however, it cannot be said that the presence of the oceanographic features confirms the validity of the models.

## 2. Objectives

The first goal of this study is the detailed description of structure and flow in the surveyed region. In particular, this description is intended to give increased definition to the distribution of southern water and to relate this to the patterns of flow viewed with similar definition.

In addition, attention will be given to secular variations, to the process by which southern water is diluted, and to the use of geostrophy in depicting small flow features.

Finally, there are more general and long-range objectives for which this study may serve as a first step. These include the accurate estimation of the transport of southern water in the counter current; the linking of this transport to come useful index, as has been done by Quinn (1974) in relating El Niño to a measure of intensity of the atmospheric easterlies, or to an "upwelling index" of coastal winds such as that compiled by Bakun (1974); and a measure of the coherence and phase between events at different points along the counter current.

## 3. Procedure and instrumentation

The observations providing the study's data base were made during two cruises: (1) of the oceanographic research vessel DE STEIGEUR, operated by the U.S. Navy Oceanographic Office, in August 1972, and (2) of ACANIA, the oceanographic vessel of the Naval Postgraduate School, in August 1973. The primary tools for the observations were the continuous profiling STD and parachute drogues tracked by radar.

On each cruise, a Bisset-Berman continuous profiling instrument (STD) was used for delineating the vertical distributions of temperature and salinity, reversing thermometers and Nansen bottle samples providing independent measurements for comparisons of temperature and salinity for calibration. The sampling intervals transverse to the flow were 5.5 km. or less (see Fig. 2) and in the direction of flow less than 20 km. The vertical definition at the rate of drop of the STD, about 30 meters per minute, is estimated to be a few meters or less. Profiles were recorded for both descent and ascent of the STD so that, during digitizing of the analogue traces, spurious spikes in the salinity record could be recognized. These spikes are associated with poorly matched time constant between the sensors for temperature and conductivity used to calculate salinity. Salinity spikes which are of opposite sign as between up and down traces are assumed to be spurious due to the mismatch and are eliminated. On both cruises independent measurements of temperature and salinity were made, respectively, with reversing thermometers and with laboratory conductivity analysis of sea water samples taken from Nansen bottles attached to the conducting wire just above the STD. These independent measurements were used for field calibration of the STD; they are considered to provide sufficient standardization of the STD data for the qualitative descriptions of structure and

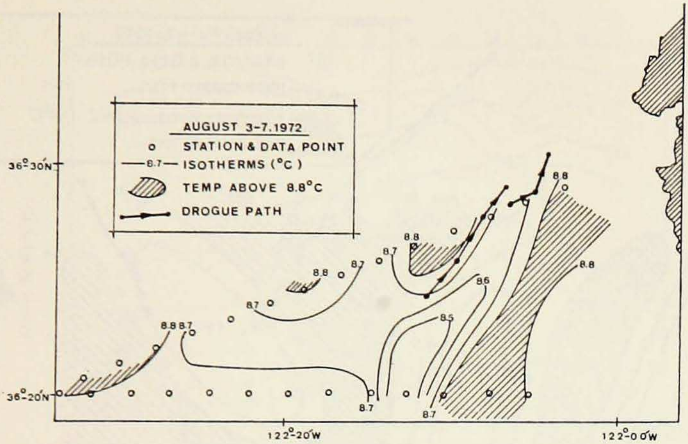

Figure 3. Temperature on surface $\sigma_t = 26.5$ and drogue paths at depth 200 meters, 3–7 August, 1973.

flow for which they are used here. Surface (bucket) temperatures were also recorded for this purpose, and some expendible bathythermograph (XBT) drops were made for further comparisons. Some gaps in STD data resulting from malfunction or in the interest of time-saving were filled with temperature data from XBT soundings.

On both cruises the drogues used were parachutes 8.5 meters in diameter. They were suspended from styrofoam floats by quarter inch polypropylene line at depths of either 50 or 200 meters. The line was held taut by concrete ballast weighing 55 kg. in air. With this weight in water, the maximum stretch of the line is about 6%. A radar target and a flashing light were attached to poles projecting above the float. The drogues were tracked by ship's radar, and on the 1972 cruise, their positions relative to the ship were estimated from radar ranges and bearings on the above-water targets. The ship's positions were usually found from multiple radar fixes on prominent shore points, but in some cases on the 1972 cruise from radar fixes on a deep moored buoy set near the lauch point of the drogues. On the 1973 cruise, most drogue positions were established when the ship and drogue locations were virtually the same. No correction for drag of the pole-float-and-line assembly was made, there being surprisingly little shear in the water column.

The position of the ship in each cruise was well established by multiple fixes so that an error of as much as 2 km. in locating a drogue is taken to be unlikely (except for the most distant drogues in 1973). Since the total drogue displacement during one day's drift was of the order of 20 km, the displacements and current speeds averaged over that period of time are estimated at the very worst to be in error by less than 20%. The probable error for the same averaging interval is much smaller and for averaging over a few days drift, smaller still. The resulting accuracy is taken to be sufficient for showing the significant features of the flow patterns. The drogue

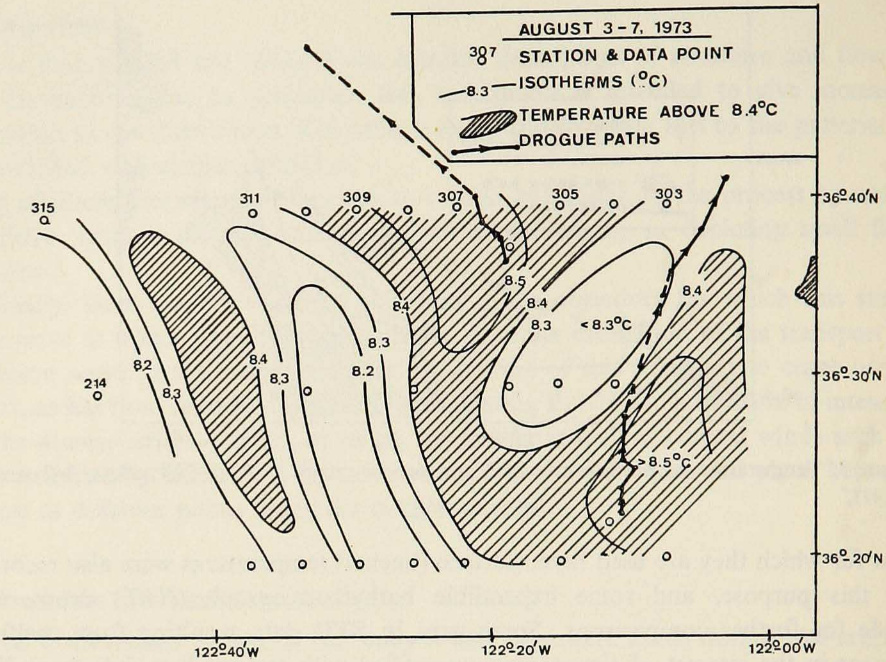

Figure 4. Temperature on surface $\sigma_t = 26.5$ and drogue paths at depth 200 meters, 3–7 August, 1973.

data have not been analyzed for high frequency components although at some stages of drift positions were recorded at intervals sufficiently close to define tidal, inertial and shorter oscillations.

## 4. Results and discussion

The description of the counter current region will be given in terms of these characteristics introduced in the section on objectives: the form of the intrusions of southern water, the patterns of flow, the relation between flow and structure, possible secular variations of these, and mixing processes.

Consider first the structure of the Southern water elements. Analysis of the temperature (or salinity) structure in this region indicates that the distribution of southern water is markedly complex. In Figures 3 and 4 temperature distributions are shown on surfaces of constant $\sigma_t$ (26.5), which are near depth 200 m, for the cruises of August 1972 and 1973, respectively. The distributions are given on these surfaces (as opposed to level surfaces) in order to emphasize variations related to the quasi-horizontal advection of contrasting water masses and to suppress those associated with vertical advection due to internal waves and upwelling. The surfaces with the chosen $\sigma_t$ are near the depth at which undercurrent water is likely to be found. In each year, as shown by the hatched areas of the two figures, there are at least two

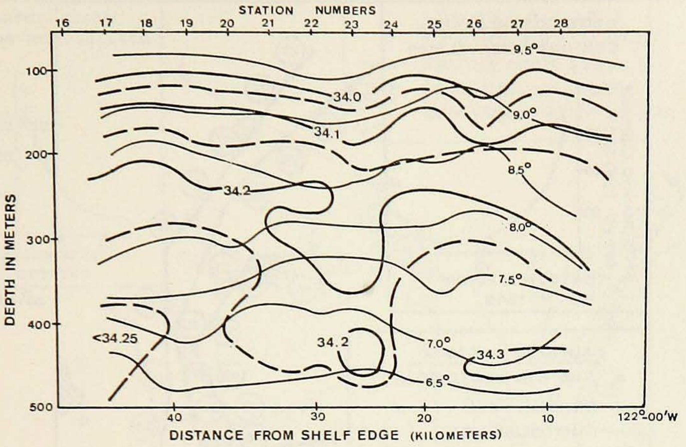

Figure 5. Temperature °C) and salinity (⁰/₀₀) on a vertical section at latitude 36°20′ N, 3–7 August, 1972.

notably warmer regions, i.e., water with "southern" characteristics. These warm areas have the appearance of intrusions from the south. They are 10–20 km. in width and may be more than 50 km. long in the direction of the flow, although their orientation and longitudinal extent cannot be unambiguously inferred from this grid of data points. The amplitude of the temperature variation on this surface is

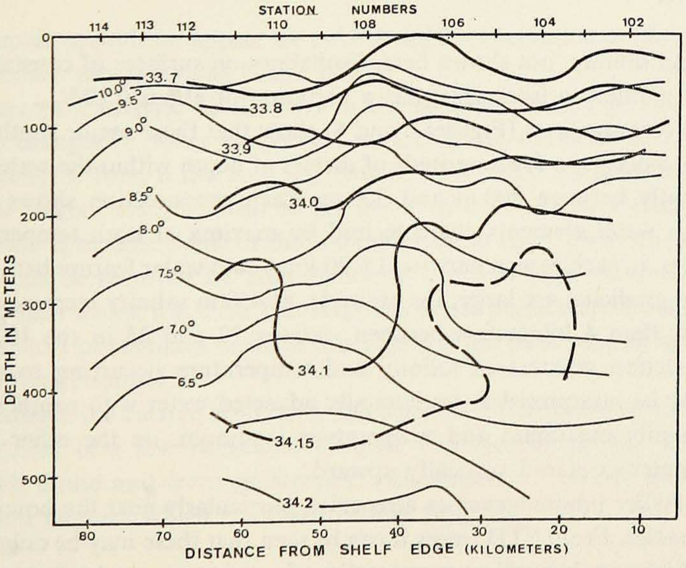

Figure 6. Temperature (°C) and salinity (⁰/₀₀) on a vertical section at latitude 36°20′ N, 3–7 August, 1973.

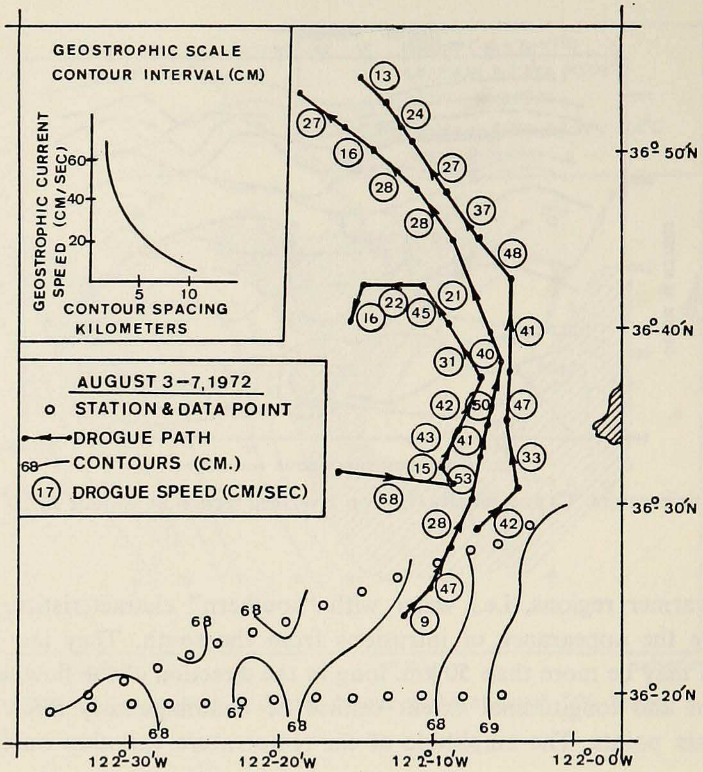

Figure 7. Relative topography of the 50/500 decibar surface and drogue drifts at depth 50 meters in August, 1972.

about 0.5°C and salinity, not shown here, (isohalines on surfaces of constant density are essentially parallel to isotherms) has a variation of about $0.10\,^0/_{00}$.

The vertical cross-sections (Figures 5 and 6) show that these major southern water elements tend to occupy a few hundreds of meters of depth within the water column, most prominently between 200 m and 500 m. Each cross-section shows two such major southern water elements characterized by maxima of both temperature and salinity. There is, in each case, a narrow (15–20 km.) cold water feature between them. The horizontal gradients are large; for example, at 450 m salinity increases by about $0.10\,^0/_{00}$ in less than 4 kilometers between stations 22 and 23 in the 1972 survey. In this cross-section maxima in salinity and temperature occurring together at a given level may be interpreted as horizontally advected water with southern characteristics. A salinity maximum and temperature minimum, on the other hand, are indicative of water displaced vertically upward.

Physically smaller inhomogeneities also exist, particularly near the boundaries between water masses. From STD traces it can be seen that these may be only a few tens of meters in thickness, but still have anomalies of temperature and salinity as large as those of the thicker layers. In some cases these thin anomalous elements are hori-

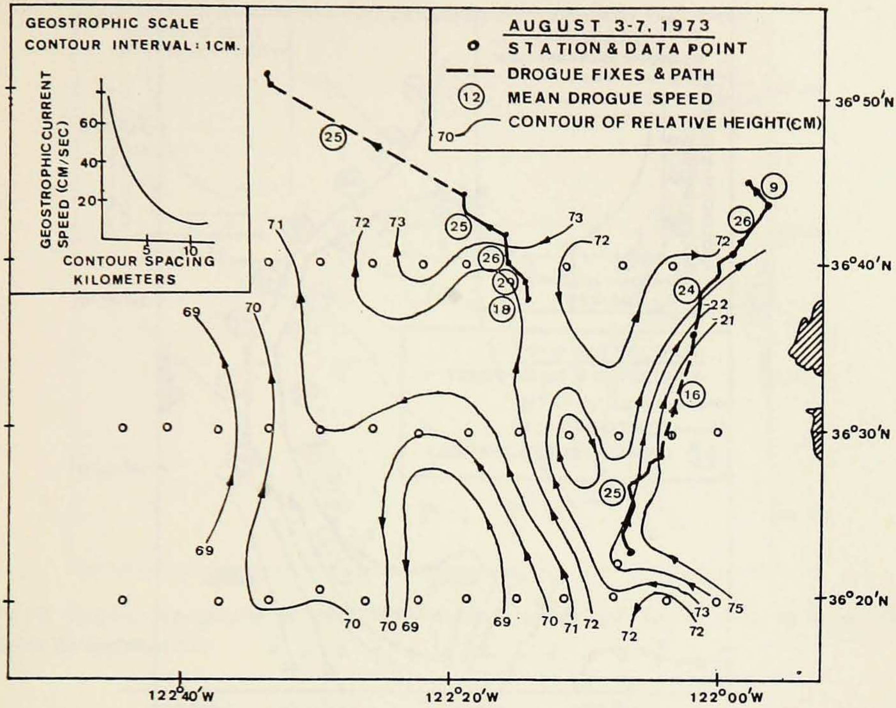

Figure 8. Relative topography of the 50/500 decibar surface and drogue drifts at depth 50 meters in August, 1973.

zontally small enough to appear at only a single observation station. Others must be lost between sample points in the grid.

In summary, transverse to the flow in the countercurrent region, there are large amplitude changes in water properties, reflecting the intrusion of southern water, with wavelengths from a few to a few tens of kilometers. Longitudinal wavelengths seem to be larger. The thickness of the layers in which these variations occur is a few hundreds of meters. Some of the ambiguity about the form of the southern water intrusions can be removed by examination of the flow patterns to be treated next. In view of these scales, it is clear that large errors are possible in assessing the volume of the transport of southern water in this region if the transverse sampling interval is larger than five kilometers.

Now consider the current structure. The patterns of current flow are inferred from the trajectories of a few parachute drogues deployed at depths 50 m and 200 m during each cruise and from geostrophy with respect to the 500 db surface. There are common features which are clear in both August patterns:

(1) At both 50 m and 200 m geostrophy indicates that there is a narrow band of poleward flowing water near the shelf edge.

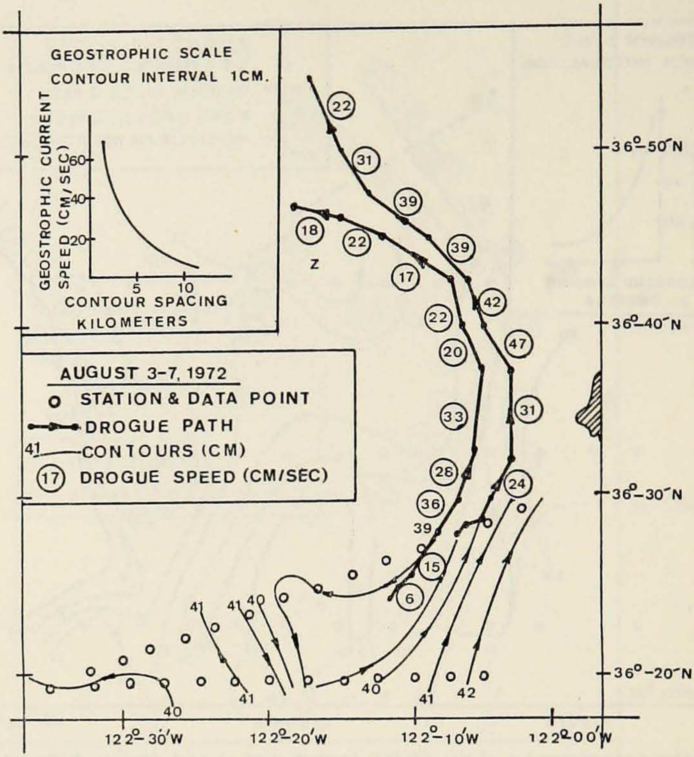

Figure 9. Relative topography of the 200/500 decibar surface and drogue drifts at depth 200 meters in August, 1972.

(2) There is complex flow to the west of that which seems to split the poleward flow into two branches.

(3) There is a broader poleward flow still farther west centered at 40–50 km. from the shelf edge.

Drogue trajectories, especially in 1972, confirm the first two of these features; and the 1973 drogue paths tend to confirm the last. The Figures 7 and 8 show the 50 db contours, with drogue trajectories at depth 50 m superimposed, for 1972 and 1973 respectively; Figures 9 and 10 are the 200 db and 200 m results for those years in the same order. Table 1 and 2 summarize the the drogue drifts giving the average speeds between selected points for the cruises of 1972 and 1973, respectively.

The mean poleward velocity across the section has a geostrophic component of less than 10 cm/sec with respect to the 500 db surface even at the depth of its maximum development (Fig. 8); but that there are intense bands of this flow is borne out by the drogue speeds, especially near Point Cypress, where the stream is narrower as if constructed by the ridge in the underwater topography. In these narrow bands, the drogues show average poleward speeds sustained over a few tens of kilometers of 20 cm/sec or more. In 1972 in the region of transversal convergence off Point

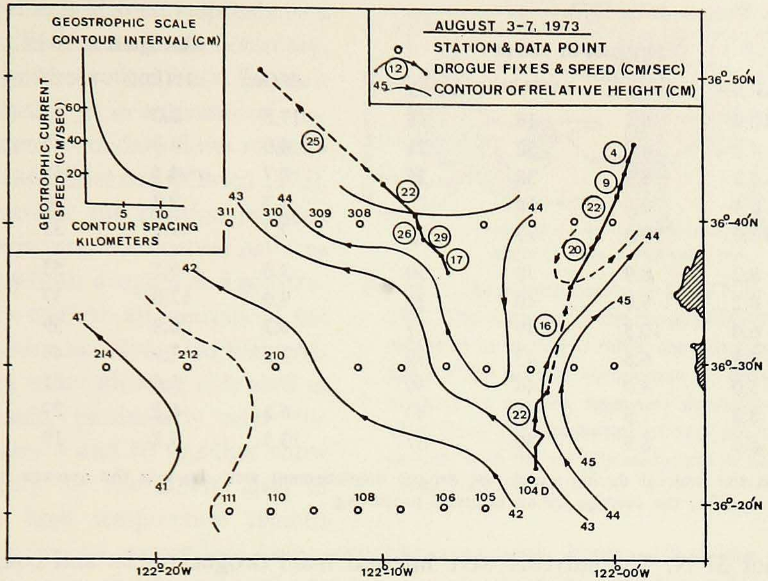

Figure 10. Relative topography of the 200/500 decibar surface and drogue drifts at depth 200 meters in August, 1973.

Cypress the mean over a 20 km. path exceeds 40 cm/sec. The local geostrophic current speeds agree only roughly with the drogue speeds. This is not surprising, for there are obvious non-geostrophic components shown in the drogue speed values averaged over rughly 10 km. intervals. These vary erratically especially near Monterey Canyon where large internal waves are known to exist. Deformations of the reference isobaric surface (500 db) also must contribute to the difference between actual flow and the results of geostrophy.

The nearly closed cyclonic trajectory traced by a drogue at depth 50 m in 1972 tends to support the idea, based largely on accumulated knowledge of dynamic topography, that the central California region (Brown 1974) of the counter-current is one in which eddies are common. It is not clear whether the eddies suggested by the dynamic topographics alone, as seen in Figures 7–10, are real or are artifacts related to the random redistributions of the field of mass by vertical motions of internal waves (Defant 1950). There is a general correspondence between the indications of the major features of the flow given by geostrophy and by the Lagrangian representation, the drogue tracks; but there are insufficient areas where both measurements are available and suitably matching for the conclusion to be reached that the geostrophy can be uncritically accepted as representing the real flow in detail. There are, however, other reports of eddies in the California current system similar in scale to that tracked by the drogue at 50 m and in approximate geostrophic balance. One example is given by Reid, Schwartzlose and Brown (1963) off Baja California

Table 1. Drogue drifts 1972.

| | Drogues at 200 m | | | | Drogues at 50 m | | | |
|---|---|---|---|---|---|---|---|---|
| | *$\Delta t$ (hr) | $\Delta s$ (km) | $v$ (cm/sec) | $\bar{v}$ (cm/sec) | $\Delta t$ (hr) | $\Delta s$ (km) | $v$ (cm/sec) | $\bar{v}$ (cm/sec) |
| WESTERN PAIR | 12.9 | 8.1 | 18 | 18 | 17.5 | 8.0 | 13 | 13 |
| | 4.2 | 4.8 | 32 | 21 | 4.0 | 4.3 | 30 | 16 |
| | 4.2 | 5.7 | 38 | 25 | 2.7 | 4.4 | 45 | 19 |
| | 6.3 | 8.7 | 38 | 28 | 4.7 | 9.8 | 58 | 26 |
| | 12.0 | 10.0 | 23 | 26 | 7.7 | 9.1 | 33 | 27 |
| EASTERN PAIR | 8.2 | 8.9 | 30 | 30 | 3.6 | 6.5 | 53 | 53 |
| | 6.2 | 9.0 | 40 | 35 | 9.0 | 12.0 | 37 | 42 |
| | 6.0 | 10.5 | 49 | 37 | 6.3 | 8.8 | 39 | 41 |
| | 4.3 | 6.6 | 43 | 39 | 3.3 | 5.9 | 49 | 42 |
| | 5.0 | 8.0 | 44 | 40 | 3.8 | 5.6 | 41 | 42 |
| | 5.2 | 7.6 | 41 | 40 | 6.5 | 6.3 | 27 | 39 |
| | 8.3 | 8.9 | 30 | 37 | 13.5 | 9.2 | 19 | 33 |

*$\Delta t$ is the interval during which the drogue displacement was $\Delta s$, $v$ is the average speed in that interval, and $\bar{v}$ is the average for all intervals preceding.

at about 31°N. The currents were inferred from drogue tracks and confirmed by geostrophy. The time history of such eddies is not known.

The vertical structure of the flow is illustrated in Fig. 11, which gives the geostrophic component with respect to the 500 decibar surface across the 36°20′N parallel of latitude in August 1972. Poleward flow (shown by unhatched areas) dominates the first 20 km from the shelf edge with some indications that it is an undercurrent, since the maximum lies below the surface. The speed 20 cm/sec is characteristic of that flow down to about 300 m. To the west, geostrophy indicates an intense equatorward jet (max. speed 80 cm/sec) at about 25 km from the shelf edge, and still farther west another poleward flow with speed near 20 cm/sec. There is reason to consider the equatorward jet and its associated strong shears realistic,

Table 2. Drogue drifts 1973.

| | Drogues at 200 m | | | | Drogues at 50 m | | | |
|---|---|---|---|---|---|---|---|---|
| | *$\Delta t$ (hr) | $\Delta s$ (km) | $v$ (cm/sec) | $\bar{v}$ (cm/sec) | $\Delta t$ (hr) | $\Delta s$ (km) | $v$ (cm/sec) | $\bar{v}$ (cm/sec) |
| WESTERN PAIR | 2.9 | 1.9 | 18 | 18 | 2.7 | 1.9 | 20 | 20 |
| | 3.3 | 3.5 | 30 | 24 | 3.3 | 3.5 | 30 | 25 |
| | 3.9 | 3.7 | 26 | 25 | 3.9 | 3.7 | 26 | 26 |
| | 6.8 | 5.3 | 22 | 24 | 6.8 | 5.5 | 23 | 24 |
| | 27.7 | 25.5 | 26 | 25 | 27.7 | 26.0 | 26 | 25 |
| EASTERN PAIR | 13.3 | 10.7 | 22 | 22 | 13.3 | 12.2 | 26 | 26 |
| | 22.9 | 13.3 | 16 | 19 | 22.9 | 13.0 | 16 | 19 |
| | 10.1 | 7.3 | 20 | 19 | 10.1 | 8.9 | 24 | 20 |
| | 7.2 | 5.9 | 23 | 19 | 7.2 | 7.0 | 27 | 21 |
| | 7.1 | 2.4 | 7 | 18 | 7.1 | 2.2 | 9 | 20 |

*$\Delta t$ is the interval during which the drogue displacement was $\Delta s$, $v$ is the average speed in that interval, and $\bar{v}$ is the average for all intervals preceding.

since the jet axis also corresponds to a sharp front-like water mass boundary. There is also theoretical basic for such an equatorward jet in a dynamical model for eastern boundary flows recently developed (McNider and O'Brien 1973).

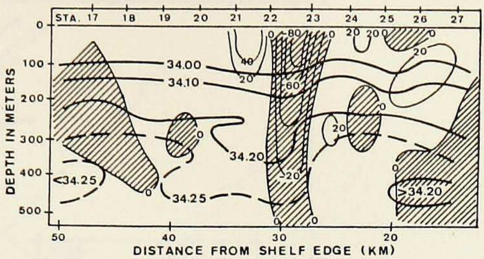

Figure 11. East-west section at 36°20′N in August 1972. The contours in the range 34.00–34.15 are salinities in parts per mille; the other contours are for the normal component of geostrophic velocity in cm/sec, negatives denoting southward flow. The southward jet does not coincide entirely with the salinity minimum in the depth range 200–400 m.

Now consider the relation between flow and structure. The current patterns indicated by both drogues and geostrophy tend to confirm an analysis of the structure which has elongated filaments of southern water flowing poleward in narrow bands, particularly near the coast. Figures 4 and 10 together show this tendency for the 200 m level in 1973, with high temperature regions and densely spaced streamlines being roughly congruent. Figure 12 shows 200 m temperatures with the drogue paths at the same depth. A few XBT stations in the northern portion of the field show consistently that warm water lies to the right of the drogues, cold to the left.

But the mixing and mutual entrainment of southern and California Current waters is also evident. In Fig. 11 a cross-section of salinity is shown superimposed on the field of isotachs of geostrophic current. Although in the region near the shelf edge the southern water (saline) does coincide with poleward flow, a part of the equatorward jet as inferred from geostrophy also includes southern water; and part of the low salinity core, according to this geostrophic view, has been entrained with the poleward flow. It is in this region of strong horizontal shear that the erosion of the southern water filament is taking place with transverse scales of mixing of the order of 10–20 km.

Now compare the observed structure and flow in 1972 with the 1973 observations. The cross-sections of Figures 5 and 6 show that there is warmer and saltier water present at almost all levels in August 1972 than in the following year; the speed of the northward flow near the shelf is much greater in 1972 (Tables 1 and 2); and the temperatures on a given surface of constant density (See Figs. 3 and 4) are higher in 1972. These observations are all consistent with a decrease in the nortward transport of southern water between 1972 and 1973; and it is of interest that the local yearly upwelling index of Bakun (1974), largely a measure of the intensity of winds from the north, increased markedly between those two years.

Another interesting temporal change was observed in the southern water characteristics between a survey in June of 1972 (Molnar 1972) at Monterey and that in August of that year. In June, a survey with grid length less than 4 km. revealed no water with southern characteristics near shore off Monterey down to depth 500 m;

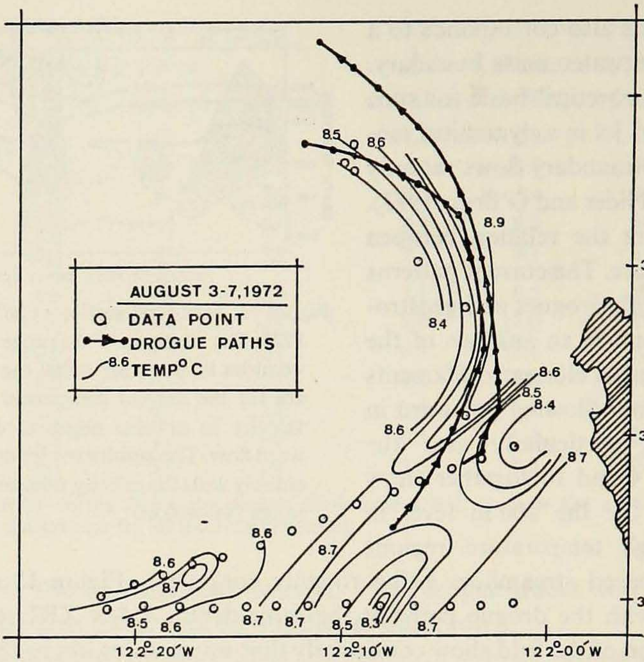

Figure 12. Isotherms and drogue paths at depth 200 meters suggesting a narrow stream of high temperature water moving cyclonically about a cold core.

but it is clearly present in August of that year. As Fig. 13 shows, this water has very nearly the characteristics of the southern water observed near Santa Barbara (as far north as Pt. Arguello) in June, suggesting that its arrival at Monterey might have been predicted by choice of an appropriate advecting speed; any speed in excess of 5 cm/sec would permit arrival in Monterey by early June.

A point is to be made about the above temporal changes and the manner of sampling. The point is that the southern water elements in each case were sufficiently small that only in surveys with sampling grid lengths of less than 10 km. transverse to the current could there be assurance that the southern water properties were realistically depicted. Some such scale of sampling thus seems to be required for the construction of a data base suitable for describing the behavior of the southern water and its associated current system.

## 5. Mixing processes

As southern water is transported northward it does undergo mixing with its surroundings, become more dilute the farther it moves from its tropical source. There remains a question about the processes which contribute to the mixing on significant scales. Among the choices are breaking internal waves, vertical instability and horizontal eddies. Internal waves cannot be dealt with by the methods of this survey, but analysis of stability is possible.

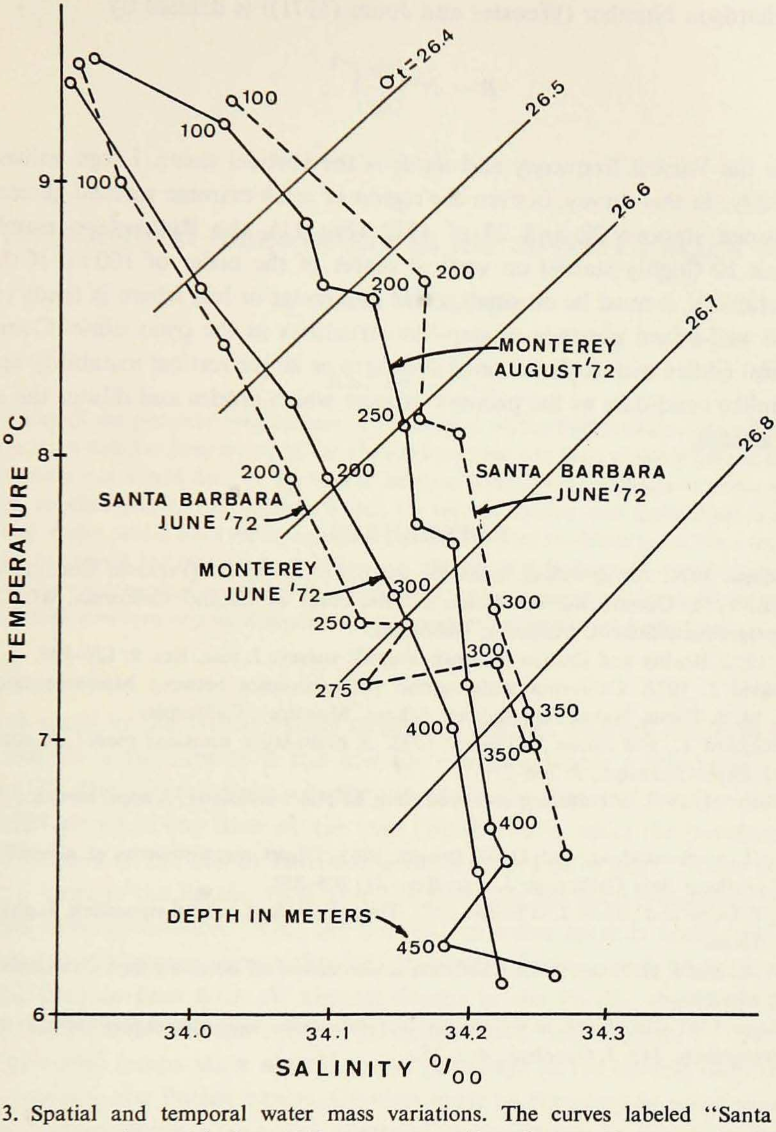

Figure 13. Spatial and temporal water mass variations. The curves labeled "Santa Barbara" represent waters observed in June 1972 on opposite sides of a transition zone about 5 km wide, the more "southern" water (upper right line) inshore and extending to about 25 km offshore only from Points Arquello southward. Off Moneterey, in a 25 km band in the same month, only the "northern" water was observed; whereas in August in that region there was water with nearly the southern characteristics (see curve labeled "Monterey, August 1972") of the water found more than two months earlier off Arquello. The southern water off Monterey in August appears to have been advected from at least as far south as Point Arguello.

The Richardson Number (Wooster and Jones (1971)) is defined by

$$R = N^2\left(\frac{du}{dz}\right)^{-2},$$

where $N$ is the Väisälä frequency and $du/dz$ is the vertical shear. Large values of $R$ imply stability. In this survey, in even the region of most extreme vertical geostrophic shear, between stations 22 and 23 of 1972 (Fig. 11), the Richardson number is greater than 20 (highly stable) on vertical scales of the order of 100 m. If there is vertical instability, it must be on small scales of a meter or less where $N$ tends toward zero in the well-mixed portions of step-like structures in the pycnocline. Compared to horizontal eddies with scales of ten kilometers or larger vertical instability appears to be an unlike candidate as the primary process which erodes and dilutes the southern water stream.

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