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Direct Measurements of a Small Surface Eddy Off Northern Baja California

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ABSTRACT

An extensive study of surface currents off northern Baja California, using parachute drogues, has confirmed the inshore sweep of surface waters that has been a major feature of the geostrophic flow in this area. Calculations of geostrophic flow from concurrent density measurements are in excellent agreement with the drogue trajectories, and an extra hydrographic cast made at the center of an eddy that was indicated earlier by the drogue movements confirms the remarkable small-scale coherence of the density and velocity fields. Eddies having the dimensions of this one may be common features in the surface circulation of the California Current. They may sometimes be the result of offshore transport during upwelling or of horizontal shear between the main stream and the countercurrent; in this case, however, neither upwelling nor countercurrent was apparent near the eddy observed. Conceivably the eddy may be a surface effect of the submerged coastal countercurrent, with possible upward transfer of momentum in the inshore areas.

Introduction. A peculiar feature in the geostrophic circulation of the California Current off northern Baja California is the shoreward sweep of the southeastward-flowing waters as they reach about 32°N, with part of the water turning northward (Fig. 1) and another part turning southward along the coast. In the region 30°—32°N, the surface waters apparently flow southward throughout the year, even in the winter months when a countercurrent appears inshore along most of the California coast. Northward flow at 31°N in winter is not clearly seen in the geostrophic flow, nor is it indicated by the movement of drift bottles in this region.

The geostrophic approximation reveals that the subsurface near-shore countercurrent does exist at depths below 200 m in this area, just as in the rest of the California Current. It also indicates that the shoreward turn of the offshore water is very much reduced at 200 m depth and that the geo-
Figure 1. Surface flow (geopotential anomaly of the sea surface with respect to the 500-decibel surface, in dynamic meters) of the California Current in four seasons.

Geostrophic flow at and below 200 m is more nearly parallel to the coast, with fewer irregularities than are seen in the surface geostrophic circulation.

Because of these peculiarities it was resolved to measure directly the surface shoreward flow. Not only was the shoreward flow well confirmed but a small eddy about 90 km in diameter was observed by both direct and geostrophic measurements.

Measurements. The surface currents were measured in October 1959, using parachute drogues of the type described by Jennings and Schwartzlose (1960). Thirty-nine parachute drogues were released from the HORIZON at 9.3-km intervals in an L-shaped pattern beginning 120 km offshore at 32°15'N and extending southward 185 km, then eastward 176 km to within 40 km of the coast. Each drogue had 10 m of wire from the surface float to the parachute. The northernmost five drogues were seen only once after their release, and six new drogues were released a few miles east of the original line to replace the lost drogues. Twelve deep drogues with 100–1000 m of wire were released at four locations.

The drogues were tracked by the HORIZON from 12 to 21 October and
by the U.S.S. Persistence from 12 to 16 October. Later the Horizon returned and located several of the drogues on 27 and 28 October. A few of the drogues were observed and reported at later dates by fishing and naval vessels.

Winds varied normally through the month. They were from the northwest and ranged from nearly calm to Beaufort force five. Sea conditions were good enough for effective radar tracking of the drogues except on 19 and 20 October.

Navigational aids are lacking in the region of the measurements. Positions were obtained as frequently as possible, but these were limited to celestial observations and to radar and visual fixes on land features when these were near enough. The accuracy of individual fixes on the drogues is therefore limited. The errors were not cumulative, however, since good fixes could be made at least once a day, and most of the drogues moved far enough during the survey so that the positional errors are small compared with the total movement.

**Results.** The movement of the drogues is shown in Figs. 2, 3, and 4. The measurements were highly successful in that nearly all of the drogues were observed long enough for useful results. The shoreward movement indicated by previous estimates of geostrophic flow is clearly seen (Fig. 1). Drogues released as far as 160 km offshore were observed to move to within 55 km of the coast. An eddy was encountered and observed for several days.

The speed of the drogues in the shoreward-moving group averaged about 21 cm/sec between 14 and 21 October; some of them traveled more than 110 km. The speed of the drogues in the eddy cannot be known precisely. Since they were not observed continuously, the number and radii of the circuits drawn in Fig. 3 cannot be known exactly. The estimated speeds vary from about 21 to 36 cm/sec and the periods of the circuits from about 88 hours near the center to about 134 hours at the edge.

Many of the deeper drogues also were observed over an adequate period for estimating their motion (Fig. 5), although the shallower drogues were given priority in searching. The observed movements at the deep drogues were corrected for windage and wire drag (Volkmann et al., 1956). The average speeds were about 15 cm/sec at 100 m, 10 cm/sec at 300 m, 8 cm/sec at 500 m, and 5 cm/sec at 1000 m.

**Comparison with the Geostrophic Flow.** The geopotential anomaly at the sea surface with respect to the 500-decibar surface was calculated from concurrent measurements (8–30 October) by the California Cooperative Oceanic Fisheries Investigations (Fig. 6). When the cyclonic eddy was discovered, a supplementary hydrographic station was made on 22 October near the estimated
center of the eddy. The geopotential anomaly at the sea surface at this location was 5 dynamic cm lower than at the nearest scheduled grid station.

Bathythermograph observations were made at 9.3-km intervals along the
ship's track beginning 75 km before, and ending 75 km beyond, the eddy station; the results suggest that the hydrographic station within the eddy (Fig. 7) was the extreme position in this series. The radius of the eddy (that is, the distance from the extreme low in geopotential anomaly to the nearest high) in either direction along the line was about 35–45 km. The vertical section of bathythermograph data intersects the drogue line in several places. The slope of the isotherms at each intersection was in the expected sense if the drogue velocities are assumed to be in geostrophic equilibrium.

The indicated geostrophic flow observed on the concurrent California Cooperative Oceanic Fisheries Investigations cruise (Fig. 6) is similar to what has been observed in previous measurements. There was a southeastward flow over the offshore area and a northwestward flow off southern California.
North of Point Conception (35°N) the northward-flowing Davidson Current of the winter season had already begun.

The geopotential anomaly within the region of the drogue measurements is shown in detail in Fig. 7, with the general movements of the drogues indicated by arrows. The most interesting single feature is the cyclonic eddy.
It is clearly indicated by the geopotential anomaly in Fig. 7. However, without the extra station (the 0.94-dynamic m value) that was taken on the basis of the drogue movements, this eddy would have slipped through the mesh of the station grid, though several others (seen in Fig. 6) did not slip through.

The differences in geopotential anomaly between the eddy station and the two adjacent stations (Fig. 8) suggest that the rotation was confined to the upper 125 m. These differences in geopotential do not stem from differences in the mixed layer (Figs. 8b and 8c), since temperature, salinity, density, and the thickness of the mixed layer (45 m) are not extreme there (Figs. 8 and 9). The difference results from a steepening of the vertical gradients in the pycnocline, so that the temperature, salinity, and density found between 80 and 125 m at the adjacent stations are found between about 50 and 100 m at the eddy station (Fig. 9a–d).

A drogue was placed at the northern edge of the eddy on 27 October and observed for one day only. The drogue seemed to move northward. It was seen 83 km north of its released position by a naval vessel on 4 November. This may indicate that the eddy had moved northward or dissipated.

The geopotential anomaly of the 200-decibar surface with respect to the 500-decibar surface (Fig. 10) shows no significant evidence of the eddy. On the contrary, this field has a very simple pattern; a trough lies parallel to the coast with its axis about 185 km offshore; the deviations from this smooth pattern are about equivalent to the magnitude of the measurement error.
Figure 6. Surface flow (geopotential anomaly of the sea surface with respect to the 500-decibar surface, in dynamic meters) in October of 1959. The box includes the area of the drogue study.

Most of the deeper drogues at 300 m and at shallower depths moved in fair agreement with the 200-decibar or surface geostrophic chart. Since the casts
did not extend below 500–600 m, the deeper drogue movements cannot be compared to the geostrophic flow.

Discussion. The significant results of these measurements are a documentation of the shoreward surface current near 32°N and of the direct observation of an eddy. The latter suggests that the irregularities previously observed in the field of geopotential in the California Current are geostrophically balanced eddies. Such irregularities are quite common in this area, and eddies of this scale may contribute very significantly to lateral mixing.

McEwen (1948) has discussed an eddy near the coast of southern California. He used measurements of geopotential anomaly made at successive times in the spring of 1940 to estimate the rate of decay; he found a substantial decline in intensity after two months. Repeated measurements in this area, however,
Figure 8. Differences of the eddy station (101.50) from the adjacent inshore station (100.50) and the offshore station (100.60).

a) Geopotential anomaly, in dynamic meters referred to the 500-decibar surface.
b) Thermosteric anomaly, in centiliters/ton.
c) Temperature in degrees Celsius.
Figure 9. Vertical section across the eddy, including the eddy station and the adjacent inshore and offshore stations, in the upper 500 m.

a) Thermometric anomaly in centiliters/ton.
b) Temperature in degrees Celsius.
c) Salinity in parts per mille.
d) Dissolved oxygen content in milliliters per liter.
indicate that the eddy he was discussing is a nearly permanent feature, with coastal waters flowing northwestward between 32° and 35°N and with off-
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shore waters flowing southeastward (Reid et al., 1958). Although the eddy shows seasonal variation, it appears to be nearly permanent. It is well developed in winter but is weakest about April (Schwartzlose, in press); possibly McEwen's estimates of decay correspond to this particular slackening. If, as Sverdrup and Fleming (1941) imply, the eddy is related to the shape of the coast and the bottom topography and has been observed to be nearly permanent, then its decay rate during the slackening period may be different from that of the offshore eddies. (The northwestward flow, they point out, is east of the submarine ridge that extends southeastward from Point Conception.)

Repeated hydrographic studies by the California Cooperative Oceanic Fisheries Investigation suggest that the offshore eddies, though common, occur at different places at different times. If the eddy measured in this study is not a permanent feature, fixed to a particular bottom topography or to a relatively constant wind feature, then there are various other explanations that might be considered.

Sverdrup and Fleming (1941) have discussed the process of upwelling and the offshore movement of the colder, more saline waters that might degenerate into eddies. Munk (1950) has pointed out that the east-west variation in meridional winds off California is such that the Sverdrup transport should produce a countercurrent. If there is a substantial north-south variation in the intensity of the winds, then separate countercurrents of different strengths might occur along the coast, and these might appear as separate eddies.

The first of these explanations cannot apply in this case, since the data are for a period when upwelling does not occur. The second likewise fails of application because the countercurrent did not appear at the surface near the eddy.

A third possibility is that the eddies might be a result of horizontal shear between the countercurrent and the main stream; the sense of rotation is correct and the eddies have been observed all along the California Current. On the other hand, the particular eddy reported here was observed in the one region where a surface inshore countercurrent is rarely found and was not observed in this case. Other eddy-like features were observed at this time (Fig. 6), both north and south of the area of the drogue study. The eddies to the north do lie between the main current and the countercurrent and are cyclonic in sense. Those to the south lie in a region that did not have a clearly developed surface countercurrent, but they overlie the trough in geopotential anomaly of the 200- with respect to the 500-decibar surface (Fig. 10).

It is perhaps conceivable that the deeper countercurrent may transfer momentum upward to the surface layers, at times when, or in regions where, the surface countercurrent does not prevail, thus causing eddies to appear where neither surface countercurrents nor coastal upwelling may produce them.
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