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A subsurface warm-eddy off northern Baja California in July 2004

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[1] Upper-ocean eddies are commonly observed from remote sensing, but submerged eddies are more difficult to detect. During July 2004, a 21-day hydrographic survey in the southern region of the California Current was carried out to investigate the mesoscale variability. We observed for the first time a subsurface anticyclonic eddy off northern Baja California with the same water mass characteristics as the California Undercurrent. The core of the eddy was quasi-circular with radii of 35 km and thickness of 250 m. The maximum swirl velocity was $\sim$3 cms^{-1}. The water mass of the core of the eddy was characterized by potential temperature of 11°C, salinity of 34.5, and dissolved oxygen of 1.4 mll^{-1}. The eddy propagated westward. The subsurface warm-eddy could transport relatively saline water into the North Pacific subtropical gyre.

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1. Introduction

[2] Mesoscale eddies are commonly observed in the California Current System. Using satellite altimetry, shipboard hydrography, and surface/subsurface drifters, these eddies have been regularly mapped. By using satellite altimetry *Strub and James* [2000] illustrated the variability of mesoscale eddy activity in the California Current. From shipboard data, *Huyer et al.* [1998] found subsurface eddies off northern California and *Simpson and Lynn* [1990] observed similar features off southern California. Also, from RAFOS floats deployed in the California Undercurrent, *Garfield et al.* [1999] showed eddy motion with westward propagation.

[3] In the southern region of the California Current (off Baja California) the sea surface circulation patterns are characterized by mesoscale eddies, meanders, and fronts [*Lynn and Simpson*, 1987; *Soto-Mardones et al.*, 2004; *Espinosa-Carreon et al.*, 2004]. In this region, mesoscale eddies are most frequently observed in boreal summer. For example, in July 2001 the surface velocity field was strongly perturbated by three eddies along the California Current main axis [*Schwing et al.*, 2002]. A large cyclonic eddy centered at 117°W, 27.5°N was detected in July 2002 [*Venrick et al.*, 2003], and its properties were described by *Soto-Mardones et al.* [2004]. On the other hand, to our knowledge, no subsurface eddy has previously been reported off Baja California.

[4] In this paper, we use satellite altimetry and shipboard hydrographic data to describe the mesoscale field in July 2004 off Baja California. We found a subsurface warm-eddy with the same water mass characteristics as the California Undercurrent. The anticyclonic eddy is similar to those eastern boundary formed eddies documented by *Huyer et al.* [1998] and *Simpson and Lynn* [1990]. Since the eddies are an efficient mechanism for offshore transport of slope water with high spiciness, the recurrence of subsurface eddies off Baja California must be very important in the large-scale salinity distribution of the North Pacific subtropical gyre.

2. Data and Methods

[5] Between 9 and 29 July 2004, a survey (hereinafter referred to as 0407) aboard the Research Vessel *Francisco de Ulloa* off Baja California was carried out as part of the Investigaciones Mexicanas de la Corriente de California (IMECOCAL) program. IMECOCAL is an ongoing observational program which started in the summer of 1997, and continuous quarterly surveys have been carried out since then. The sampling grid of IMECOCAL is a reduced CalCOFI grid off Baja California (Figure 1a). Spacing between stations is approximately 37 km and between lines is approximately 74 km. At each station CTD casts are taken from the surface to 1000 m depth, using a Sea-Bird CTD. Temperature, conductivity, and oxygen sensors are factory calibrated prior to each survey.

[6] In the 0407 survey all stations were successfully sampled. Following *Davis* [1985] and *Le Traon* [1990] objective mapping (optimum interpolation) was used to estimate the thermodynamic variables from repeated hydrographic observations (32 cruises). A three-dimensional box with 18-km resolution in the horizontal and 1-m resolution in the vertical was developed. The correlation scales for the x-y (across and along coast) plane were 100 km in x-direction and 125 km in the y-direction, and for the x-z plane in the z-direction was 80 m. The geostrophic method was used for calculating the relative velocities referenced to 1000 dbar (1 bar = 10^5 Pa). The eddy's relative vorticity, ξ (φ, r), where φ is the polar angle and r is the radial distance, was computed according to *Simpson and Lynn* [1990]. To compare rotation with strain, the Okubo-Weiss parameter was computed according to *Thompson and Young* [2006]. To analyze water mass origin, spiciness ($\Pi(\theta, S)$) was calculated using the method of *Flament* [2002].

3. Patterns of Surface Circulation

[7] Figure 1a shows the dynamic height anomaly for 0/1000 dbar. The sea surface circulation pattern shows a cyclonic eddy centered near 118°W, 28°N and an anticyclonic eddy centered near 117°W, 29.5°N. The main flow

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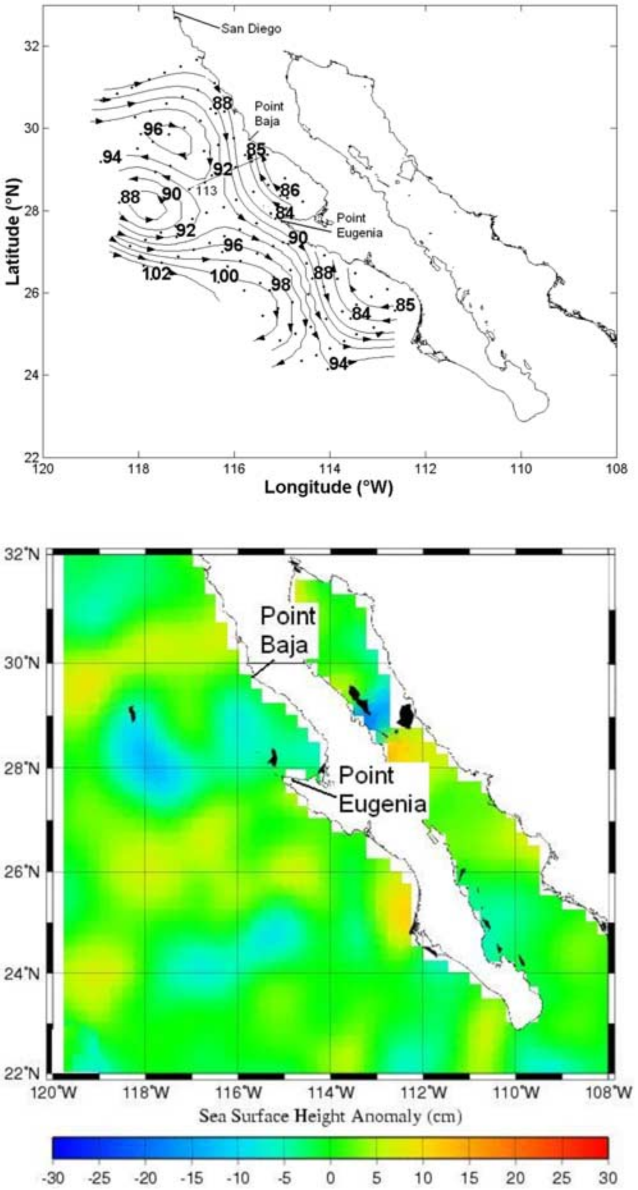

Figure 1. (a) Dynamic height from hydrographic data at the sea surface relative to 1000 dbar. (b) Sea surface height anomaly from altimetry for the period 10–20 July 2004 in centimeters. The IMECOCAL's station grid is marked with dots. The solid line marks the line 113.

of the California Current is perturbed by this dipole. The core of the California Current is deflected shoreward at 30°N. Upon reaching the coast, this flow continues equatorward with slight meandering along the coastal boundary. An outer branch of the California Current veers inshore at 27°N. North and south of Point Eugenia, between the core of the California Current and the coast there is a surface poleward flow.

[8] Figure 1b shows sea surface height (SSH) anomaly map (in cm) for the period 10–20 July 2004. The map was generated by the Colorado Center for Astrodynamics Research at the University of Colorado, Boulder. It is noteworthy that the snapshot shows a cyclonic mesoscale eddy along 28°N with the lowest SSH anomaly of ~ −15 cm. However, the signature of anticyclonic eddies (positive anomaly) is less organized, although visible along 30°N and 26°N. From the 10-day repeat T/P satellite altimetry, we estimated that the cyclonic eddy propagates to the west.

4. Patterns of Subsurface Circulation

[9] Figure 2a shows the dynamic height anomaly for 200/1000 dbar. The geostrophic flow pattern in the subsurface water column is strongly affected by mesoscale eddies. The California Current is considerably weaker at this level. An intense subsurface anticyclonic eddy centered near 117°W, 29°N and a weaker anticyclonic eddy centered near 115°W, 26.5°N are the dominant features. The cyclonic eddy is also present at this depth, although is less organized. The inshore poleward flow has similar pattern at this level as the upper one.

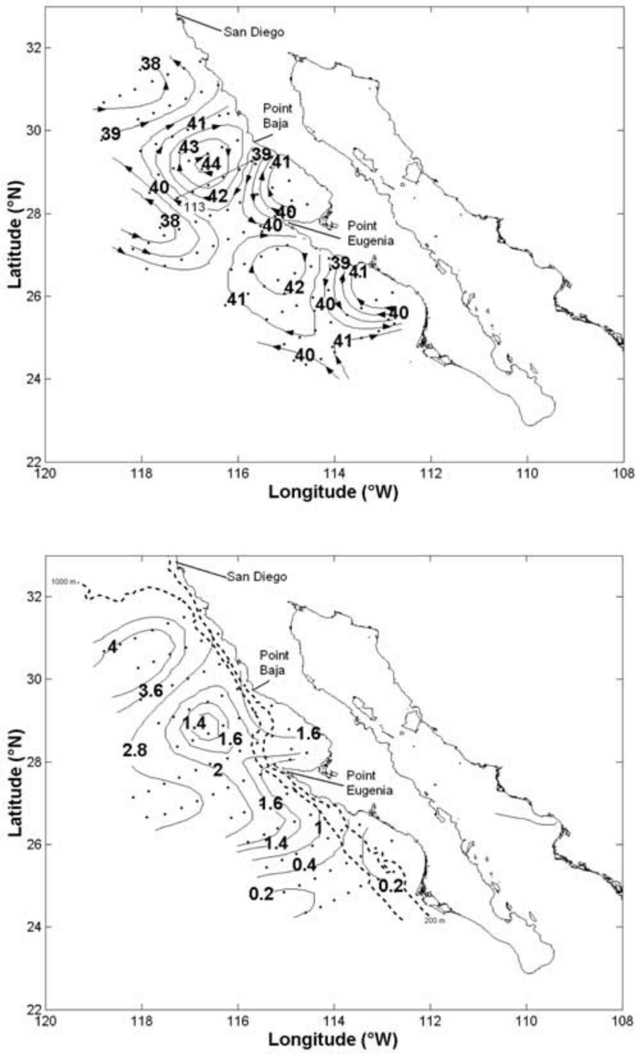

Figure 2. (a) Dynamic height from hydrographic data at 200 m relative to 1000 dbar in dynamic meters. (b) Distribution of O_2 in mll^{-1} on the surface of 10°C potential temperature. The dashed line indicates the 500-m and 1000-m depth contours. The solid line marks the line 113.

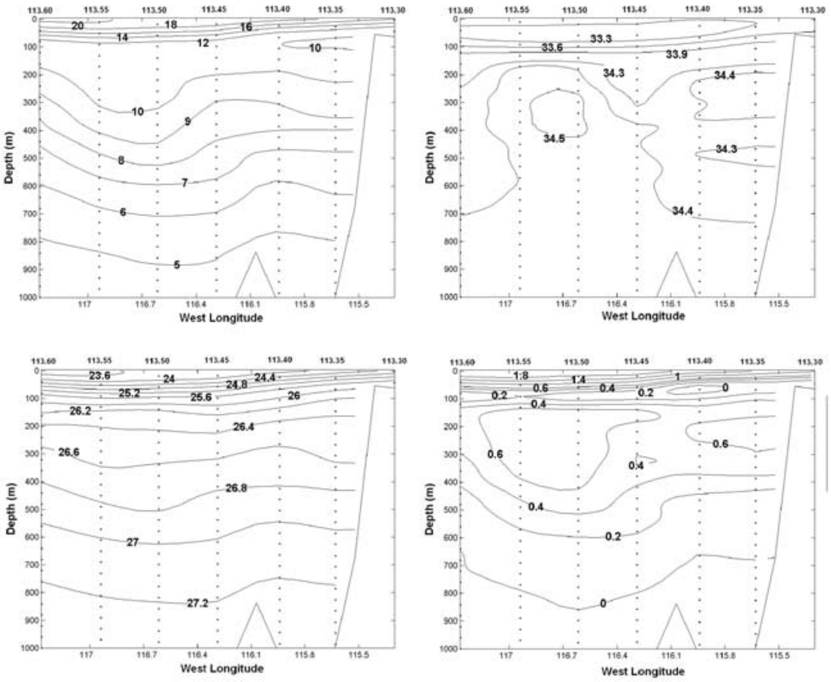

Figure 3. Vertical sections along line 113 of (a) potential temperature, (b) salinity, (c) potential density, and (d) spiciness.

[10] Oxygen provides an independent non-conservative tracer of flow. In the subsurface waters (200 m) off southern Baja California low values of oxygen (0.5–1.0 mll^{-1}) are typically found [*Reid et al.*, 1958]. Figure 2b shows the distribution of O_2 in mll^{-1}on the surface of 10°C potential temperature. This surface is deeper (320 m) at the southern region than at the northern region (120 m). From the O_2 distribution, it is noteworthy that the subsurface anticyclonic eddy is located near 117°W, 29°N. The core of the eddy (1.6–1.4 mll^{-1}) is at 220-m depth. At the north of Point Eugenia, the signature of the poleward flow (1.6 mll^{-1}) is at 120-m depth. The Okubo-Weiss parameter calculated from the dynamic height anomaly for 200/1000 dbar was negative (maximum magnitude $\sim -2.5 \times 10^{-7}\ \mathrm{s}^{-2}$) at the center of the core of the eddy identified by the O_2 distribution, which means that rotation dominated. The Π distribution on the surface 10°C (information not shown) showed the same pattern as the O_2 distribution.

5. Water Characteristics of the Subsurface Anticyclonic Eddy

[11] We present water mass characteristics of the subsurface anticyclonic eddy off Point Baja which centers at 117°W, 29°N, because of its extraordinary features. Figure 3 shows sections of θ, S, σ_θ, and Π along line 113. The seasonal thermocline is located ~50 m depth. A warm dome is a conspicuous feature between station 55 and station 45. The isotherms of 10°C and 9°C descend from station 40 to station 35. Close to the surface, a core of cold water of 10°C is centered between station 40 and station 35. The minimum of salinity (33.2) is at the center of the line to 50 m depth. The seasonal halocline is located ~ 100 m depth. A salty dome is a conspicuous feature in the salinity subsurface pattern. Between station 55 and station 50 a salty-core (34.5) is a conspicuous feature at 300–400 m depth; between station 40 and station 35 another salty-core (34.4) is present but at 200–350 m depth. The pycnocline is located between the thermocline and the halocline. Isopycnal surfaces are consistent with the warm dome at the middle of the section. The inclination of the isopycnal surface of 26.6 kgm^{-3} between station 35 and station 40 is consistent with a subsurface poleward flow. Salty and warm subsurface waters have a Π value >0.6 kgm^{-3}. The core of the anticyclonic eddy and the core of the subsurface poleward flow are water bodies with $\Pi > 0.6\ \mathrm{kgm}^{-3}$.

[12] Figure 4a shows T-S diagram for each station along line 113 with constant potential density and spiciness lines. From station 60 to station 40, the upper straight line of constant salinity is associated with water mass of the California Current [*Durazo and Baumgartner*, 2002]. The water mass of the upper layer at station 35 is colder and saltier than the rest. It is associated with water mass from below (upwelling). The lower straight line of constant salinity corresponds to North Pacific Intermediate Water's water [*Durazo and Baumgartner*, 2002]. The subsurface water is characterized by a line of constant potential temperature. In particular, the water mass of the subsurface eddy is characterized by potential temperature of ~11°C, salinity of 34.5, potential density of 26.5 kgm^{-3}, and Π value of 0.9 kgm^{-3}. At the offshore boundary of the eddy (station 60), there is no constant potential temperature layer. On the other hand, the core of the subsurface poleward flow (station 35) is characterized by potential temperature of ~10°C, salinity of 34.4, potential density of 26.5 kgm^{-3} and Π value of 0.7 kgm^{-3}.

[13] Figure 4b shows Π-O_2 diagram for each station of line 113. The water mass of the upper layer is characterized by the straight line O_2 = 6.0 mll^{-1}. On the other hand, the water mass of the lower layer is characterized by

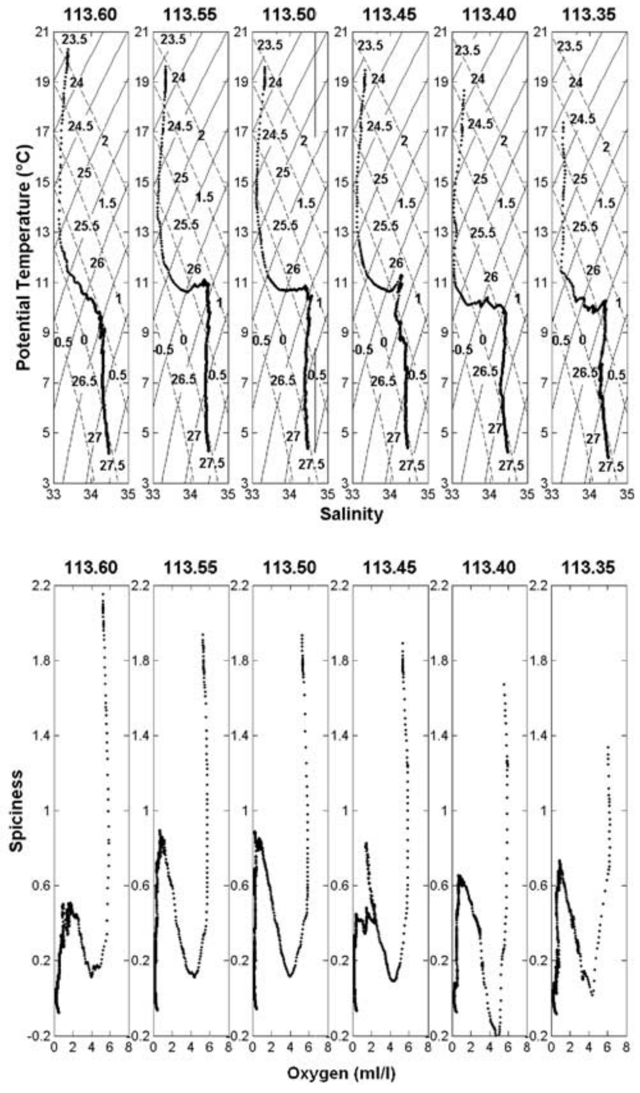

Figure 4. For line 113's stations, (a) potential temperature versus salinity with lines of potential density and spiciness and (b) spiciness versus oxygen.

low oxygen (<2.0 $\mathrm{ml l^{-1}}$). Using Π as a tracer, the core of the eddy is marked by high values of Π (>0.6 $\mathrm{kg m^{-3}}$) and low values of O_2 (<2.0 $\mathrm{ml l^{-1}}$). Similarly, the core of the subsurface poleward flow is indicated by high values of Π (>0.6 $\mathrm{kg m^{-3}}$) and low values of O_2 (<2.0 $\mathrm{ml l^{-1}}$).

6. Discussion

[14] In July 2004 eddy activity was very intense in the southern region of the California Current. A mesoscale eddy dipole was established at the upper ocean. The eddy dipole was discernible by both altimetry and hydrography. Below the mixed layer two anticyclonic eddies reached more than 200 m depth. In this work, we presented for the first time the three-dimensional structure of a subsurface warm-eddy off northern Baja California. The subsurface anticyclone eddy was no noticeable by snapshots from satellite altimetry. The core of the eddy was warm and salty, thus with high spiciness, and with low dissolved oxygen content. Similarly, the core of the subsurface poleward flow was indicated by high values of spiciness and low values of O_2. The eddy probably was generated in the continental slope by the California Undercurrent.

[15] The subsurface geostrophic current pattern shows strong horizontal currents in the continental slope at the north of Point Eugenia. Moreover, between Point Eugenia and Point Baja the slope turns northwestward (Figure 2b), which suggests that local bathymetry might trigger the development of barotropic and baroclinic instabilities of the California Undercurrent. Following *McWilliams and Flierl* [1979] and *Zamudio et al.* [2006] we compute a Beta Rossby number for the warm-eddy. This nondimensional number is defined as the ratio of relative vorticity to planetary vorticity advection $R_B = v/\beta r^2$, where v is the maximum swirl velocity and r is radius of the eddy. In this case, $\beta = 1.2556 \times 10^{-11}\ \mathrm{m^{-1}\ s^{-1}}$, $v = 3\ \mathrm{cms^{-1}}$, and $r = 35$ km. In our case, $R_B = 1.95$, which implies a role of barotropic instabilities involving the first baroclinic mode in the generation of the eddy [*Murphy and Hurlburt*, 1999; *Zamudio et al.*, 2006]. The eddy axis is characterized by a local minimum in isopycnal surface, as the potential density increases with depth; this minimum is moved toward the coast. The inclination of the isopycnal surfaces (and isothermal surfaces) suggests that the eddy is moving offshore.

[16] We found that in July of 2004 the path of the core of the California Current was modified by a mesoscale eddy dipole off Baja California. *Goericke et al.* [2005] described the state of the California Current from April 2004 to January 2005. Their map of dynamic height anomaly relative to 500 dbar captured the strong cyclonic eddy documented here. They found that the system was "normal" with respect to its climatology, and did not see, for example, any effect of the weak El Niño 2004. *Durazo and Baumgartner* [2002] studied the effect of the stronger El Niño 1997–1998 off Baja California. They found that the California Undercurrent had an increased volume transport during this event. We found that in this study the subsurface waters were dominated by subsurface warm-eddies and countercurrents. It remains to be examined whether the El Niño 2004 might have a role in this pattern.

[17] The subsurface water mass off Baja California consists of waters of both subarctic and equatorial origin [*Lynn and Simpson*, 1987; *Durazo and Baumgartner*, 2002]. The water mass of the California Undercurrent off Baja California is characterized by relatively high temperature (8–11°C) and high salinity (>34.3) [*Wooster and Jones*, 1970] and low dissolved oxygen concentration [*Lynn and Simpson*, 1987]. In this work, the California Undercurrent core is identified near the continental slope and at intermediate depths (200–400 m), with high temperature (8–10°C), high salinity (34.4–34.5), and low dissolved oxygen content (1.0–2.0 $\mathrm{ml l^{-1}}$). Therefore the water mass of the core of the eddy (station 55 and station 50) has the same signature as the California Undercurrent water. This eddy is probably a California Undercurrent mesoscale eddy comparable to those observed off northern California [*Huyer et al.*, 1998] and off southern California [*Simpson and Lynn*, 1990].

[18] Meddies (Mediterranean eddies) are a very well known subsurface mesoscale eddies. They transport salty water from the Mediterranean Undercurrent to the northeast Atlantic [*Bower et al.*, 1997]. Therefore the Meddies modify the distribution of salt at intermediate depths in the North

Atlantic. Meddies are anticyclonic features, but mesoscale subsurface cyclonic eddies also have been observed in the North Atlantic [*Zhurbas et al.*, 2004]. In our observations off Baja California, a mesoscale subsurface eddy that propagated westward was shown. *Lukas and Santiago-Mandujano* [2001] documented subsurface water mass anomalies during January 2001 at the Hawaii Ocean Time-series (HOT). They suggested that an eddy off Baja California was the source of these anomalies. In a previous work, *Kennan and Lukas* [1996] observed also at HOT frequent water mass anomalies at intermediate depths. It remains to be demonstrated whether the generation of subsurface warm eddies off Baja California is the cause for the recurrent water mass anomalies reported by *Kennan and Lukas* [1996] and *Lukas and Santiago-Mandujano* [2001] in the North Pacific subtropical gyre.

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