

OFFSHORE ENTRAINMENT OF ANCHOVY SPAWNING HABITAT, EGGS, AND LARVAE BY A DISPLACED EDDY IN 1985

PAUL C. FIEDLER
National Marine Fisheries Service
Southwest Fisheries Center
P.O. Box 271
La Jolla, California 92038

ABSTRACT

In early 1985, a recurrent anticyclonic eddy, normally located about 400 km southwest of Point Conception, was displaced toward the offshore limit of the northern anchovy spawning range in the Southern California Bight. The anomalous location of the eddy, and surface flow patterns associated with it were determined from hydrographic data and satellite imagery. Productive surface waters of 14°-15°C, characteristic of the preferred spawning habitat of northern anchovy, were entrained from within the Southern California Bight by the eddy. Eggs were found 150 km farther offshore than in 1980-84, because of a combination of spawning habitat extension and advection. The eggs and subsequent larvae were removed from the usual larval feeding grounds within the bight. This extraordinary displacement apparently had little or no effect on recruitment in fall 1985.

RESUMEN

A principios de 1985, un vórtice anticiclónico de carácter periódico, normalmente ubicado alrededor de 400 km al Sureste de Point Conception, fue desplazado hacia el límite externo de la zona de desove de la anchoveta norteña en la Bahía del Sur de California. La ubicación anómala de este vórtice, y los patrones de circulación superficial asociados con el mismo fueron determinados por medio de información hidrográfica e imágenes de satélite. Aguas superficiales productivas con temperaturas de 14°-15°C, características del habitat de desove preferido de la anchoveta norteña, fueron atrapadas por el vórtice desde el interior de la Bahía del Sur de California. Se encontraron huevos a 150 km, mar adentro, en relación a aquellos colectados en 1980-84, debido a una extensión del habitat combinada con una advección de los productos de desove. Estos huevos y las posteriores larvas fueron sacados de las áreas de alimentación larval normales en la bahía. Este desplazamiento extraordinario de los productos de desove tuvo, aparentemente, muy poco o ningún efecto sobre el reclutamiento en el otoño de 1985.

INTRODUCTION

The Southern California Bight is the center of

spawning activity for many pelagic fishes, including the large central stock of northern anchovy (*Engraulis mordax*). The bight is a particularly favorable spawning habitat, with a semienclosed gyral pattern of geostrophic flow (the Southern California Eddy) over a wide and topographically complex continental shelf; a relatively stable density structure of near-surface waters; and weak offshore Ekman transport and turbulent mixing (Husby and Nelson 1982; Parrish et al. 1983). The main axis of the California Current and the persistent eddy field seaward of that axis are normally farther from the coast along southern California than they are to the north of Point Conception (Figure 1). Peak anchovy spawning in February-April coincides with the seasonal minimum of offshore velocity in the surface mixed layer (Bakun 1985). Thus, minimizing the offshore dispersion of eggs and larvae from the coastal spawning habitat appears to be an important component of the spawning strategy of northern anchovy and other fishes in the Southern California Bight (Parrish et al. 1981).

This generalization is based on mean patterns of spawning activity and environmental variables. The Southern California Bight, however, is part of the highly variable California Current system, which is dominated by low-frequency, interannual changes in physical and biological factors (Chelton et al. 1982). Much of this variability is caused by tropical El Niño and mid-latitude warm events (Norton et al. 1985), which have had demonstrated effects on northern anchovy spawning activity (Fiedler et al. 1986).

The anchovy is a multiple spawner, with each female producing several batches of eggs per year. Eggs remain near the surface and hatch two to four days after spawning. Some spawning activity is observed year-round, but three-quarters of the yearly spawnings occur in February-April (Parrish et al., in press). Abundance and spatial distribution of anchovy eggs have been measured on biomass surveys during peak spawning months since 1980 (Figure 2. Stauffer and Picquelle 1980, 1981¹; Picquelle and Hewitt 1983, 1984; Hewitt 1985; Bindman 1986).

Substantial variations in egg distribution were caused by the 1982-84 California El Niño. In 1983 the

[Manuscript received February 12, 1986.]

¹Stauffer, G.D., and S.J. Picquelle. 1981. The 1981 egg production estimates of anchovy spawning biomass. Southwest Fisheries Center, unpublished report.

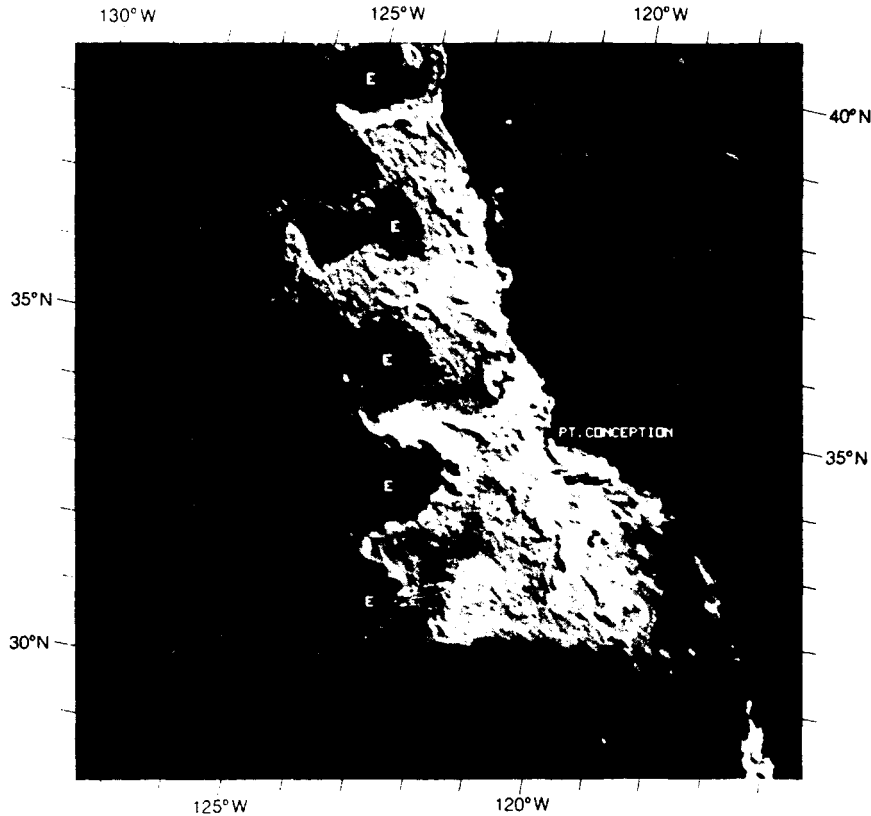


Figure 1. CZCS phytoplankton pigment image, June 15, 1981, showing a series of offshore eddies (E) in the California Current region off California. The recurrent eddy is the second from the bottom, to the left of Point Conception. Distance of eddies from coast increases north to south, from 100 to 400 km. Lighter shades indicate higher pigment concentrations on a logarithmic scale, with an additional enhancement to emphasize gradients.

boundary normally formed by the $\sim 14^{\circ}\text{C}$ surface isotherm had shifted far to the north of Point Conception; spawning range extended unusually far to the north, as well as offshore in the region of the Channel Islands. In 1984 the cold-water boundary was present, but spawning range again extended somewhat farther offshore than in 1980-82. On the 1980-84 surveys, eggs were sampled as far as 250 to 280 km from shore in the central region of the Southern California Bight (i.e., between CalCOFI lines 86.7 and 92).

The 1985 egg distribution was very unusual. First, small but significant numbers of eggs were found in cold ($< 13^{\circ}\text{C}$) water to the north of Point Conception. Then, large numbers of eggs began to be taken along line 90. Sampling was extended offshore to station 80 on lines 91.7 to 95. Eggs were found up to 400 km offshore on these lines, 120-150 km beyond the farthest offshore eggs in 1980-84.

The anomalous offshore extension of the 1985 egg distribution would have important consequences for the stock if these eggs, and the larvae hatched from them, were irretrievably lost from inshore larval feed-

ing grounds. What could have caused the peculiar egg distribution pattern? Offshore Ekman transport (coastal upwelling) is a primary mechanism of offshore transport in eastern boundary current systems. However, coastal upwelling off California is near its seasonal minimum in February and does not produce extensive coastal jets or plumes within the Southern California Bight. Another mechanism is needed to explain the observations.

An anticyclonic eddy located about 400 km SW of Point Conception is a recurrent component of the offshore eddy field of the California Current system; January-April 1949-65 CalCOFI data indicate that its mean position is 32.1°N , 123.4°W , $\pm 1.2^{\circ}$ (Simpson et al. in press). A sporadic, but not unusual, phenomenon associated with this eddy has been noted: onshore displacement may cause enhanced entrainment of cool coastal water and its associated biological community (Hauray et al. in press). In this paper, I will exploit the extensive, detailed, and repetitive coverage of the sea surface by satellite-borne sensors to locate the eddy and estimate surface flow associated with it. I wish to

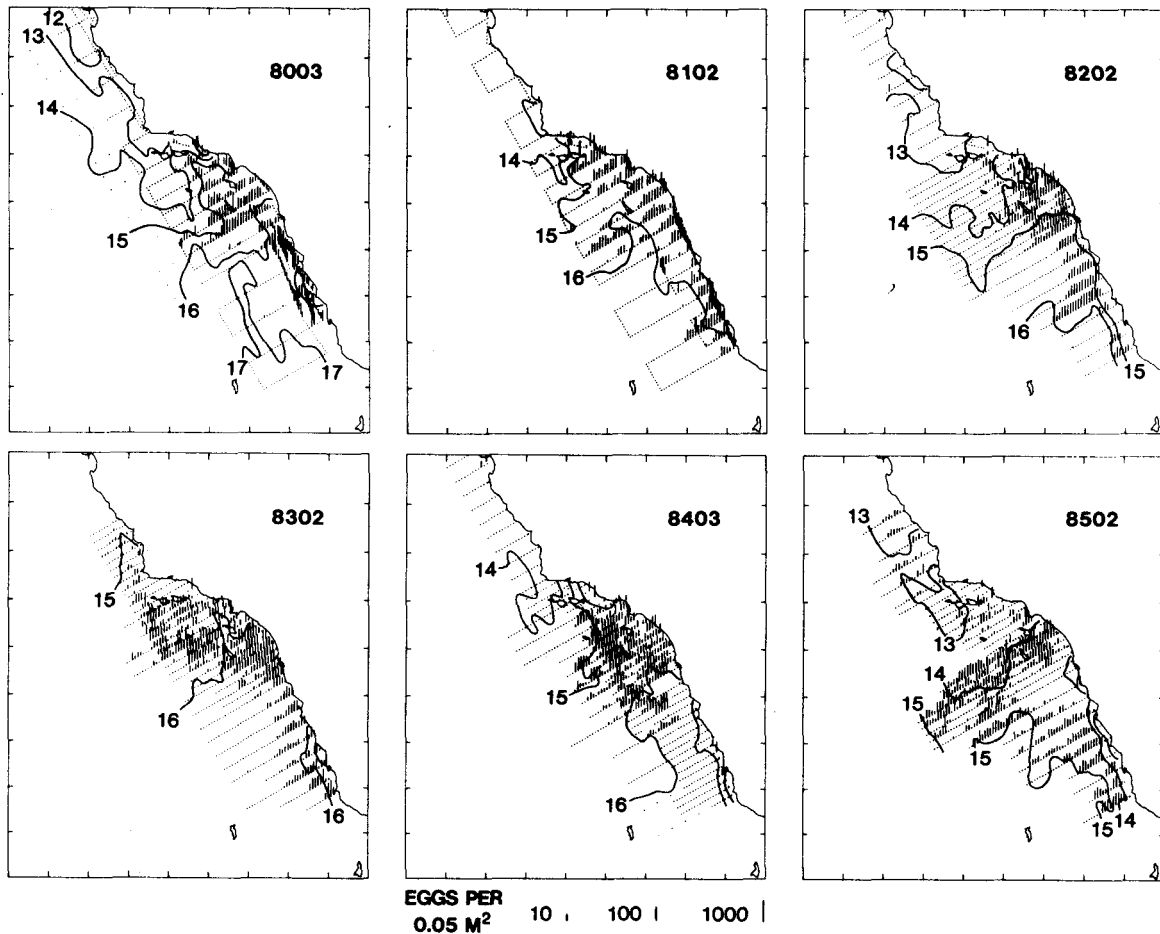


Figure 2. Surface isotherms (°C) and anchovy egg distributions on anchovy biomass cruises (CalCOFI 8003-4, 8102, 8202, 8302, 8403, and 8502). From Fiedler et al. (1986).

thank Jim Simpson for pointing out the possible manifestation of the displaced eddy in the data from CalCOFI cruise 8502.

METHODS

Satellite data were received, archived, and processed at the Scripps Satellite Oceanography Facility. Thermal infrared data from channel 4 (11 μm) of the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA-7 and NOAA-9 satellites were corrected for the effect of thin low clouds, when necessary, using channel 2 (0.7-1.1 μm) near-infrared data (Gower 1985). No further correction was implemented for absorption of sea-surface radiance by atmospheric water vapor. Although multichannel correction algorithms produce more accurate temperature estimates, they do so at the cost of amplifying the noise

in the sensor signal. Preserving small-scale patterns of sea-surface temperature variability was considered a higher priority for this study.

Visible radiance data from the Coastal Zone Color Scanner (CZCS, Nimbus-7 satellite) were processed using an algorithm based on Gordon et al. (1983) to remove effects of Rayleigh and aerosol scattering and to derive phytoplankton pigment concentrations from corrected blue/green radiance ratios. Surface flow patterns were derived by tracking movement of sub-mesoscale features in sequential AVHRR images (Vastano and Borders 1984).

RESULTS

In Figure 3, two AVHRR sea-surface temperature images show mesoscale variability off southern California in January 1984 and 1985. In both images, the

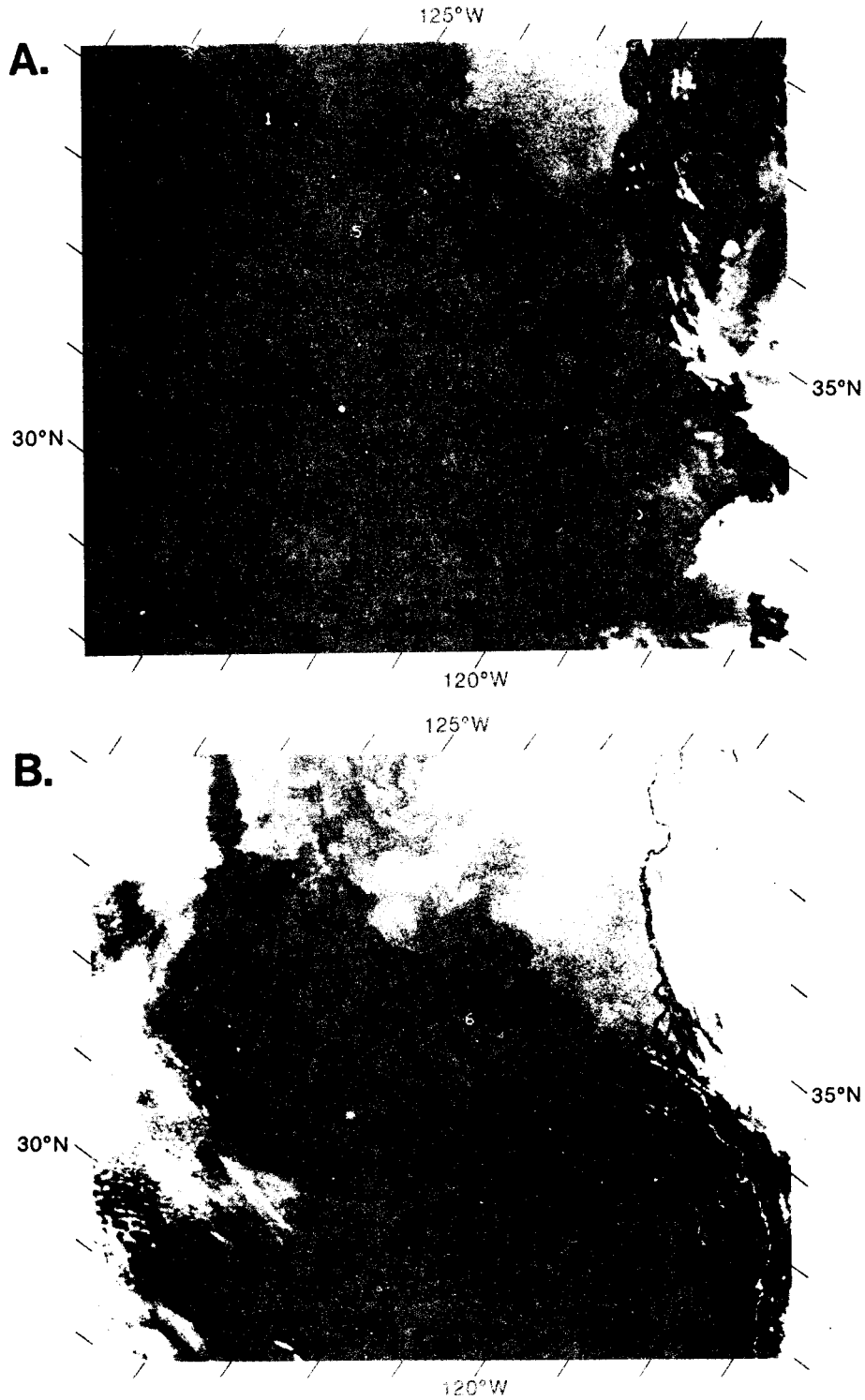


Figure 3. AVHRR sea-surface temperature images from (A) January 26, 1984 (1 = anticyclonic eddy, 2 = cold streamer, 3 = warm streamer, 4 = cold streamer from coast, 5 = secondary warm streamer) and (B) January 1, 1985 (6 = anticyclonic eddy, 7 = cold streamer from coast, 8 = cold-water plume from Point Conception). The asterisk (*) marks the mean January-April location of the recurrent eddy (Simpson et al., in press). Water temperatures range from 10.5°C (light grey) to 17°C (dark grey).

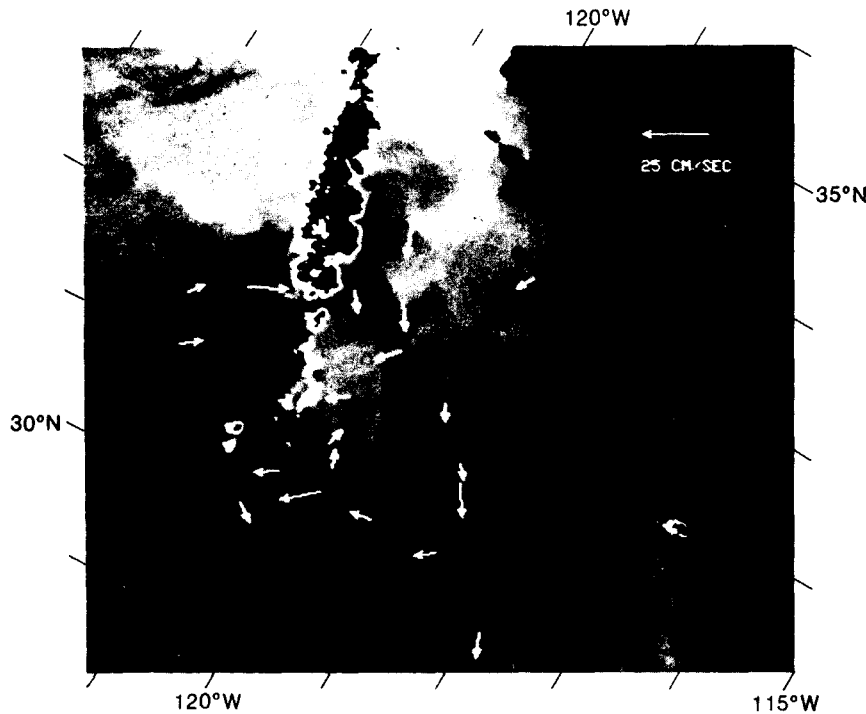


Figure 4. AVHRR sea-surface temperature image from February 21, 1985, with surface current vectors (arrows) derived from movements of submesoscale features visible on February 21 and 24, 1985. Temperatures range between 10° and 13.6°C. Clouds and land are masked with black.

coldest water (lighter grey shades) is along the coast to the north of Point Conception. This is California Current water augmented by seasonally weak coastal upwelling. The cold surface water extends south of Point Conception as a streamer or plume that separates from the coast. This pattern is obscured by clouds in Figure 3a, but is clearly visible in Figure 3b, where warmer nearshore water in the Southern California Bight can also be seen. The warmest water in both images is found to the south and offshore.

On January 26, 1984, a warm-water anticyclonic eddy is clearly visible at 34.2°N, 126.4°W (Figure 3a). This is 360 km northwest of the mean historical position, at the extreme of the range observed by Simpson et al. (in press). A well-defined cold streamer, with a source outside the image to the north, is wrapped around the inshore side of the eddy. A warm streamer from an offshore, oceanic source is wrapped around the offshore side of the eddy. The temperature of surface water within the eddy is intermediate between the temperatures of the surrounding warm and cold streamers. A large cold streamer (~400 km long) extends from the coast north of Point Conception out toward the eddy. Instead of becoming entrained by the eddy, this streamer is deflected to the south around a secondary warm streamer surrounding the inshore edge of the eddy.

On January 1, 1985, a warm-water anticyclonic eddy is at 33.8°N, 122.5°W—370 km east of the January 1984 eddy and 210 km northeast of the mean position (Figure 3b). A cold streamer flowing along the southern edge of the eddy is anchored on the coast in the vicinity of Point Conception and can be traced almost 500 km offshore. Some water from within the Southern California Bight appears to be entrained in this streamer.

On February 21, 1985, the eddy was located at 32.6°N, 122.5°W (Figure 4). It was then 130 km south of its position on January 1 and 100 km east-northeast of the mean position. A surface velocity field derived from the February 21 and 24 images is included in Figure 4. Current vectors were more easily measured at the edges of the eddy than in the cool coastal water mass inshore of the eddy, because the submesoscale features serving as tracers are most visible at strong temperature gradients. Although cloud cover prevented complete coverage of the eddy, and the discernible flow pattern is complex, anticyclonic rotation is apparent on the northern and inshore edges, where velocities are 7-15 cm/sec, dominated by an offshore component of 7-10 cm/sec.

Figure 5 is a Coastal Zone Color Scanner image showing that the cool coastal water being entrained offshore by the eddy was relatively rich in phytoplank-

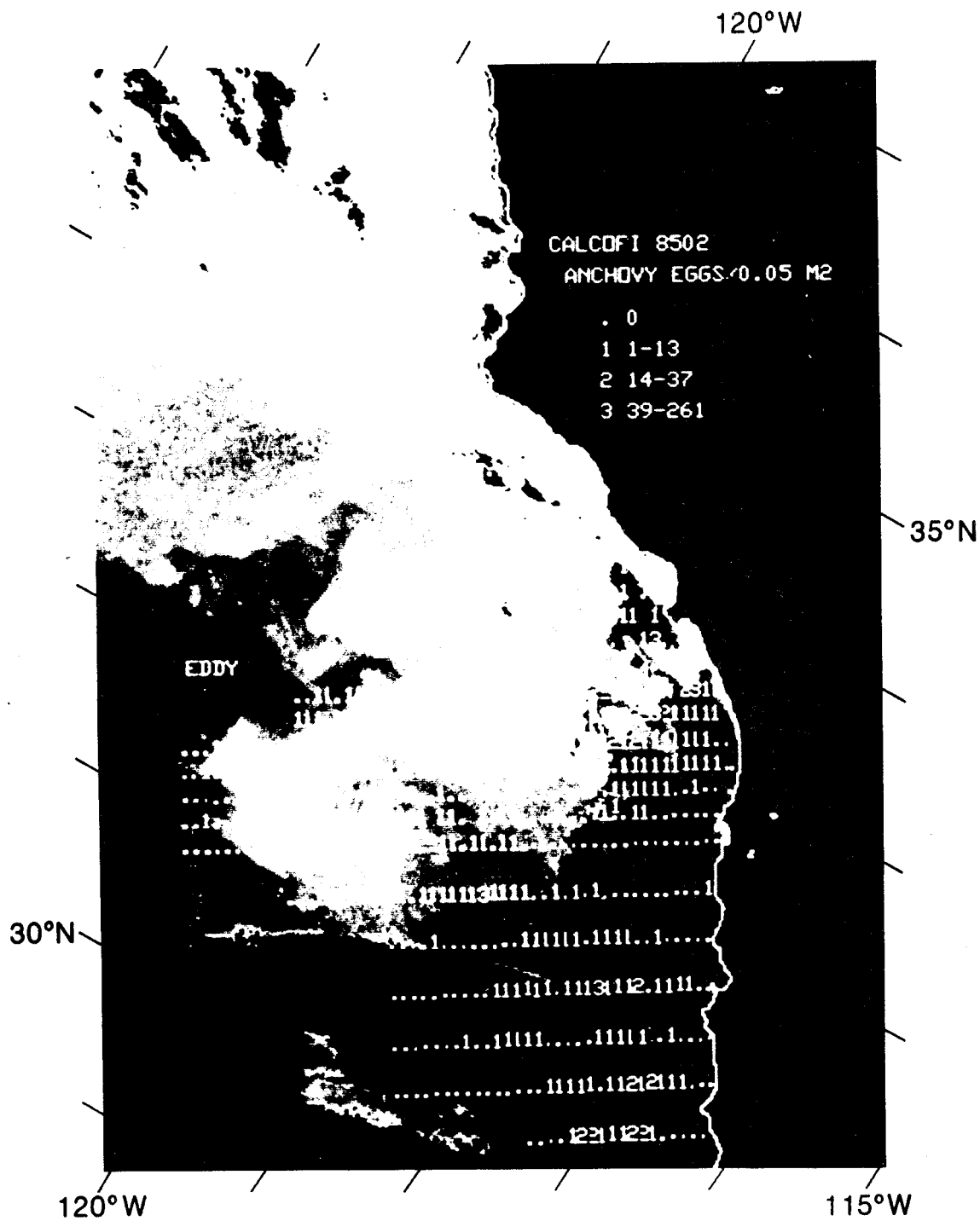


Figure 5. CZCS phytoplankton pigment image from February 28, 1985. Pigment concentrations range between 0.12 and 4.7 mg m⁻³ (dark to light). Clouds and land are masked with black. Relative abundance of anchovy eggs in vertical egg tows (CALVET) on CalCOFI cruise 8502. R.V. *David Starr Jordan*, January 28-March 8, 1985.

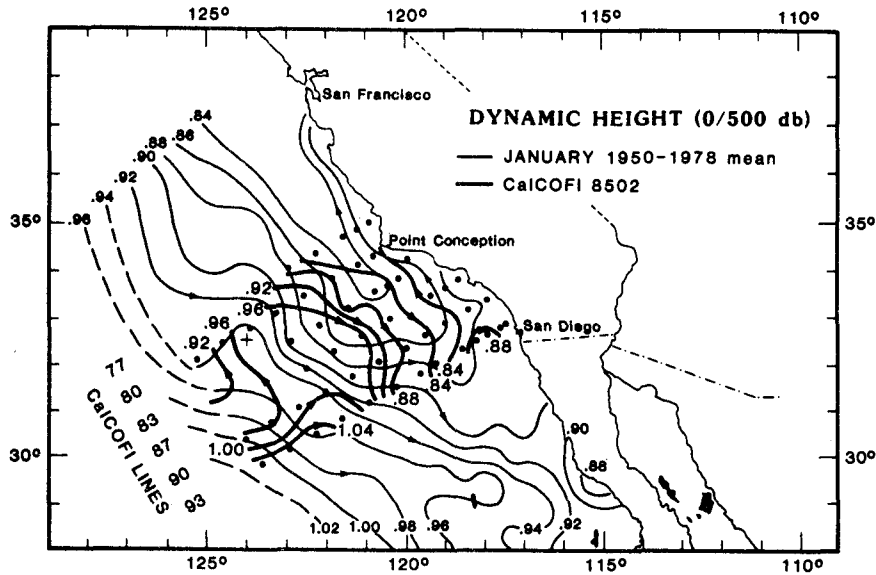


Figure 6. Dynamic height and geostrophic flow at the surface: January 1950-78 mean (Lynn et al. 1982) and CalCOFI cruise 8502, February 19-March 5, 1985 (Scripps Institution of Oceanography 1985). + = mean position of recurrent anticyclonic eddy (Simpson et al., in press).

ton pigment. The offshore extension of anchovy eggs is contained in this cool, rich surface water. Note, however, that there are few eggs in the even colder and richer water to the north toward Point Conception.

DISCUSSION

In the mean January hydrography, this recurrent anticyclonic eddy appears as a local elevation in dynamic height within a geostrophic current meander (Figure 6), and as local depressions of isopycnal surfaces ($\sigma_t = 25.0$ in the top of the thermocline at ~ 80 m; $\sigma_t = 25.8$ at ~ 140 m; and $\sigma_t = 26.6$ at ~ 280 m; Lynn et al. 1982). Dynamic topography at the sea surface in February 1985 shows an unusual pattern of meanders centered at 32°N , 122°W (Figure 6). The local high, and the direction of flow on three sides of it suggest that the eddy was embedded within this pattern. The revised CalCOFI grid, with no offshore sampling between lines 80 and 90, unfortunately missed the center of this eddy. However, the data show the enhanced entrainment of coastal water expected from such a displacement: the direction of surface flow at coastal stations along CalCOFI lines 90 and 93, inshore of the eddy, was more offshore than the long-term mean. The observed egg distribution is consistent with entrainment in anomalously strong offshore flow associated with the displaced eddy: the offshore extension of anchovy eggs is within the region of anomalous offshore flow.

Power (in press) analyzed larval anchovy drift from the spawning center in the Southern California Bight. His 30-day simulation model of advection-diffusion

incorporated mean seasonal geostrophic currents and Ekman transport and a constant eddy diffusivity. In March, most larvae move inshore from the points where they were spawned. Monthly mean offshore Ekman velocities in the bight range between .05 and 2.0 cm/sec, assuming negligible Ekman transport below 50 m (Husby and Nelson 1982). Power found that significant seaward transport of larvae occurred only if Ekman velocities were increased to three times the long-term mean, or up to 6 cm/sec.

During an intensive study in January 1981, the anticyclonic eddy was located at 32.4°N , 124°W and was found to be entraining both cold coastal waters and warm oceanic waters into its surface and near-surface layers. In this "normal" case, the source of the coastal waters was north of Point Conception (Simpson et al. 1984). Satellite imagery shows that this eddy was displaced 100-200 km inshore of the normal position in January and February 1985. Surface waters from within the Southern California Bight were entrained toward the eddy. Apparent offshore velocities were up to 10 cm/sec, or five times greater than normal mean offshore Ekman velocities.

Eggs that hatch in three days could move only 30 km at this speed. Therefore, anomalous advection of eggs cannot entirely explain the 150 km offshore extension. Spawning must have been taking place offshore of the normal range. Ken Mais provides maps of major concentrations of adult anchovies in the central stock from February acoustic and midwater trawl surveys of the central stock (California Department of Fish and Game Cruise Reports 80-A-1, 81-X-1, 82-X-1, 83-X-1, 84-

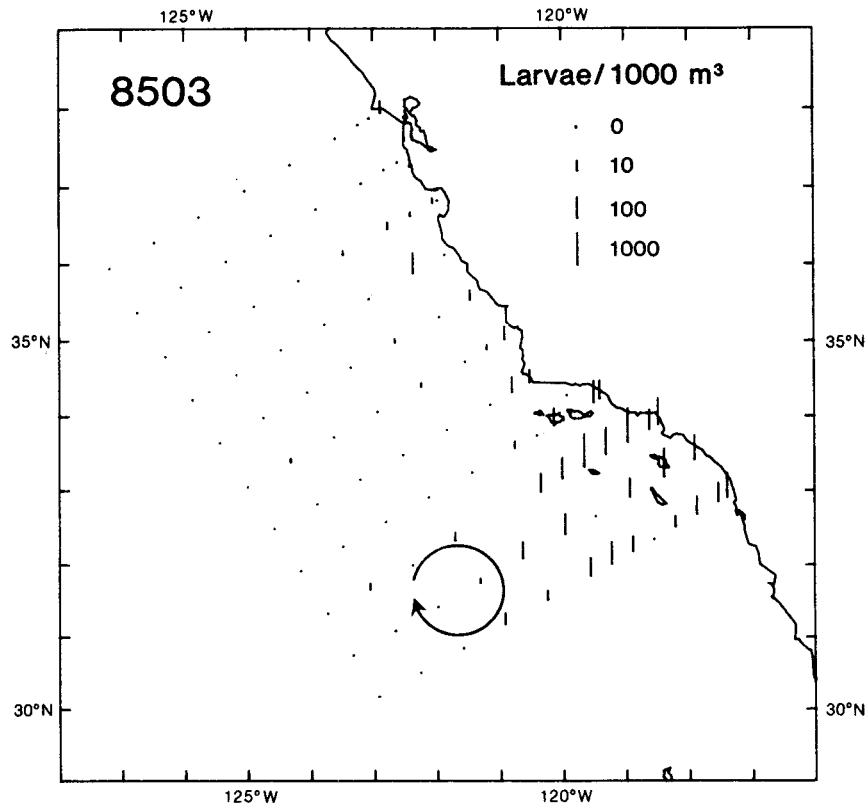


Figure 7. Anchovy larvae abundance from bongo net tows, 333- μ m mesh, on CalCOFI cruise 8503, R/V *McArthur*, March 15–April 5, 1985. The location of the eddy on February 21, 1985, is indicated schematically.

X-1, and 85-X-1). These maps show a maximum offshore extent of anchovies of 230 km in 1985, compared with 80-190 km (mean = 142 km) in 1980-84. Mais reported that the 1985 distribution was more offshore and southward than in any previous survey, and that "the bulk of the population was located in an arc of 80 miles west to south, and 30 miles east to south of San Clemente Island." This distribution encompasses the region of anomalous offshore flow illustrated in Figure 6.

Adult spawners in winter 1985 moved offshore within the cool coastal water mass being entrained by the displaced eddy. The eggs spawned by these fish were advected for a short distance by this offshore flow. We can assume that offshore advection continued as the eggs hatched and larvae developed. Ultimately, the larvae may have been trapped in the surface convergence within the eddy or spun off to the south and offshore. A few larvae were found offshore in the vicinity of the eddy in March 1985 (out to station 100 on line 87; Figure 7). Unfortunately, no sampling was done south of the U.S.-Mexico border.

Available evidence indicates that the displacement of spawning habitat and products had little, if any,

effect on recruitment of the 1985 anchovy year class. Central stock spawning biomass in February 1985 was about average for the post-1979 period (Bindman 1986). A September California Department of Fish and Game anchovy recruitment survey north of the U.S.-Mexico border found evidence of a relatively weak 1985 year class: mean catch rate of juveniles ranked seventh among nine surveys conducted since 1976 (K. F. Mais, California Department of Fish and Game Cruise Report 85-X-14). A limited trawl survey in February-March 1986 again found a relatively small proportion of 1985 year-class fish (K. F. Mais, California Department of Fish and Game Cruise Report 86-X-4). However, the year class appeared relatively strong in the Ensenada fishery south of the border in fall 1985 (R. Methot, Southwest Fisheries Center, pers. comm.).

The best estimate as of April 1986 is that the 1985 year class is neither stronger nor weaker than expected from the 1985 spawning stock. Two major environmental perturbations in recent years—the 1982-84 California El Niño and the displaced offshore eddy in 1985—have caused observable changes in central stock spawning activity without a resultant effect on

stock size. The northern anchovy seems to be resistant to such perturbations, perhaps because of compensatory responses in the juvenile stage that we are only beginning to sample adequately.

ACKNOWLEDGMENTS

I thank the many NMFS scientists, technicians, and ship personnel who contributed to the sampling and analysis involved in the anchovy egg production surveys, as well as the staff of the Scripps Satellite Oceanography Facility (SSOF) for receiving and archiving satellite data. SSOF activities are partially funded by a NSF/NASA/ONR block grant to the Scripps Institution of Oceanography.

LITERATURE CITED

- Bakun, A. 1985. Comparative studies and the recruitment problem: searching for generalizations. Calif. Coop. Oceanic Fish. Invest. Rep. 26:30-40.
- Bindman, A. 1986. The 1985 spawning biomass of the northern anchovy. Calif. Coop. Oceanic Fish. Invest. Rep. 27:(this volume).
- Chelton, D.B., P.A. Bernal, and J.A. McGowan. 1982. Large-scale inter-annual physical and biological interaction in the California Current. J. Mar. Res. 40:1095-1125.
- Fiedler, P.C., R.D. Methot, and R.P. Hewitt. 1986. Effects of California El Niño 1982-1984 on the northern anchovy. J. Mar. Res. 44:317-338.
- Gordon, H.R., D.K. Clark, J.W. Brown, O.B. Brown, R.H. Evans, and W.W. Broenkow. 1983. Phytoplankton pigment concentrations in the Middle Atlantic Bight: comparison of ship determinations and CZCS estimates. Appl. Optics 22:20-36.
- Gower, J.F.R. 1985. Reduction of the effect of clouds on satellite thermal imagery. Int. J. Remote Sensing 6:1419-1434.
- Haury, L.R., J.J. Simpson, J. Peláez, and C. Koblinsky. In press. Biological consequences of a recurrent eddy off Point Conception, California. J. Geophys. Res.
- Hewitt, R.P. 1985. The 1984 spawning biomass of the northern anchovy. Calif. Coop. Oceanic Fish. Invest. Rep. 26:17-25.
- Husby, D.M., and C.S. Nelson. 1982. Turbulence and vertical stability in the California Current. Calif. Coop. Oceanic Fish. Invest. Rep. 23:113-129.
- Lynn, R.J., K.A. Bliss, and L.E. Eber. 1982. Vertical and horizontal distributions of seasonal mean temperature, salinity, sigma-t, stability, dynamic height, oxygen, and oxygen saturation in the California Current, 1950-1978. Calif. Coop. Oceanic Fish. Invest. Atlas No. 30, 513 p.
- Norton, J., D. McLain, R. Brainard, and D. Husby. 1985. The 1982-83 El Niño off Baja and Alta California and its ocean climate context. In W.S. Wooster and D.L. Fluharty, (eds.). El Niño north: Niño effects in the Eastern Subarctic Pacific. Washington Sea Grant Program, Univ. Wash., Seattle 312 p.
- Parrish, R.H., C.S. Nelson, and A. Bakun. 1981. Transport mechanisms and reproductive success of fishes in the California Current. Biol. Oceanogr. 1:175-203.
- Parrish, R.H., A. Bakun, D.M. Husby, and C.S. Nelson. 1983. Comparative climatology of selected environmental processes in relation to eastern boundary current pelagic fish reproduction. In G.D. Sharp and J. Csirke (eds.). Proceedings of the Expert Consultation to Examine Changes in Abundance and Species of Neritic Fish Resources. FAO Fish Rep. 291(3): 731-778.
- Parrish, R.H., D.L. Mallicoate, K.F. Mais, and R.A. Klingbeil. In press. Age-dependent maturation stages, sex ratio, spawning frequency and fecundity in the northern anchovy, *Engraulis mordax*. Fish. Bull.
- Picquelle, S.J., and R.P. Hewitt. 1983. The northern anchovy spawning biomass for the 1982-1983 California fishing season. Calif. Coop. Oceanic Fish. Invest. Rep. 24:16-28.
- . 1984. The 1983 spawning biomass of the northern anchovy. Calif. Coop. Oceanic Fish. Invest. Rep. 25:16-27.
- Power, J.H. In press. A model of the drift of anchovy larvae (*Engraulis mordax*) in the California Current. Fish. Bull.
- Scripps Institution of Oceanography. 1985. Data report: physical, chemical and biological data. CalCOFI cruise 8502, 19 February-5 March 1985. CalCOFI cruise 8505, 29 April-18 May 1985. SIO Reference 85-14, 94 p.
- Simpson, J.J., T.D. Dickey, and C.J. Koblinsky. 1984. An offshore eddy in the California Current system. Part I. Interior dynamics. Prog. Oceanogr. 13:5-49.
- Simpson, J.J., C.J. Koblinsky, J. Peláez, L.R. Haury, and D. Wiesenbahn. In press. Temperature-plant pigment-optical relations in a recurrent offshore mesoscale eddy near Point Conception, California. J. Geophys. Res.
- Stauffer, G.D., and S.J. Picquelle. 1980. Estimates of the 1980 spawning biomass of the central subpopulation of northern anchovy. Southwest Fisheries Center Admin. Rep. LJ-80-09.
- Vastano, A.C., and S.E. Borders. 1984. Surface motion over an anticyclonic eddy on the Oyashio Front. Remote Sensing Environ. 16:87-90.