Eddies of the California Current System: Physical and Ecological Characteristics

R. W. Owen
National Oceanic and Atmospheric Administration,
National Marine Fisheries Service,
Southwest Fisheries Center, La Jolla, California 92038

INTRODUCTION

This paper reviews eddies and their ecological effects in the California Current System (CCS). The importance of eddies lies in the physical properties of eddy motion and the effect on what we can identify to be systematic in flow patterns and in patterns of organism distribution. The Southern California Eddy (SC Eddy), which owes at least its character and perhaps its existence to the island and bank system off southern California, receives special attention because it is the most resolvable and ecologically significant eddy known in the CCS.

Many terrestrial populations as well as littoral and planktonic marine communities may prove to be continuously or temporarily maintained by eddy processes in otherwise marginal habitats. The fate of manmade products (MacGregor 1974) and their effect on island coastal and oceanic populations are also in part determined by the flow perturbations of the CCS. Formation of eddies in the flow is of particular interest since organisms and substances in transit become rather differently distributed in space and time in gyre-like circulations. Concentrations of organisms and substances are maintained in eddies at higher levels and for longer periods, their trajectories are markedly different, and populations which would not otherwise interact are juxtaposed. Recirculation by eddies further affects such local environmental conditions as temperature and nutrient distribution in the water, and humidity, temperature, and cloud cover in the atmosphere. My purpose is to give examples of eddy circulation—both free and stationary—and to show that large eddies are more a rule than an exception in the CCS, particularly in the Southern California Bight (SC Bight). I wish also to support the hypothesis that eddies larger than 10 km in diameter and longer than a week's duration have a major role in sustaining the high biological productivity which is characteristic of the inshore 200 km of the CCS.

Baroclinic eddies, meaning those identifiable from their effect on the mass field, have the interesting property of deforming the observable density field. A cyclonic eddy of sufficient size and intensity exhibits a detectable dome in surfaces of constant density to the depth where the eddy motion vanishes. This signals that the thermocline layer, which marks a sharp increase in water density with depth, has risen and displaced surface mixed-layer water, which is stripped of nutrients and usually poor in phytoplankton as well. In regions such as the CCS, where the thermocline is nutrient-laden and close to the bottom of the photic zone, this elevation results in a vertical flux of nutrients which affects growth of phytoplankton stocks. The new availability of nutrients is augmented and sustained by upwelling (here meaning upward flow across the eddy's density surfaces) in and near the eddy center and by mixing and stripping from shear flow across the thermocline layer of the eddy. Additional nutrients are supplied in episodic fashion during storm activity long or severe enough to erode the dome, with its relatively exposed pate (*e.g.*, Blackburn 1966). If such an eddy is associated with a boundary, it will also collect and conserve populations and nutrients washed down from the boundary layer of the obstacle. Seed populations in such eddies appear to respond to this major niche modification by increasing their production and biomass and thus rapidly create new sequences of community structure (*e.g.*, Sargent and Walker 1948). Closer examination of biological effects of eddies seems warranted to determine, for example, whether eddy processes can affect production and survival of the commercially and ecologically significant anchovy, *Engraulis mordax*. This may occur by eddy effect on phytoplankton community structure or on productivity, both important factors in determining survival of the large numbers of anchovy spawned in the region (Lasker 1975, Smith 1978).

THEORY AND PHYSICS OF EDDY FORMATION

A fluid of a given viscosity impinging on an obstacle produces eddies if the obstacle is large enough or if the flow is fast enough. These eddies can be stationary, "attached" to the lee side of the obstacle, or, with increased flow or obstacle size, may be shed in a series similar to a von Kármán vortex street. A vortex street, in air or water, extends as a series of paired eddies downstream from the obstacle. There exists a large body of theory on transitions from laminar flow to stationary eddy formation to eddy street formation for simple obstacle geometries in ideal fluids. Island profiles and ocean flow are neither simple nor ideal, however. In view of the complex and hazily perceived behavior of island-ocean systems of the Pacific, it is scarcely worth reviewing theory beyond the degree to which it has been helpful in describing large eddies in the sea. Irregularities in the flow impinging on the obstacle in question cause part of the complexity. In addition, interaction of small perturbations with larger ones, changes in depth and degree of density stratification, and irregular geometry of islands and shoals all contribute to the difficulty of verifying theory by measurement.

Van Dorn *et al.* (1967) investigated circulation downstream from two small, mid-Pacific islands using direct current measurements. They described from somewhat limited observations what appears to be stable shedding of eddies in the wakes of the islands. Choosing a relatively simple system, Barkley (1972) examined flow past Johnston Atoll, a small, mid-Pacific barrier, using direct current measurements by drogues and his ship's drift. He found remarkable agreement between observed current patterns and von Kármán's physical-mathematical model of flow past long cylinders, considering the simplifying assumptions that were necessary (constant impinging current velocity, no vertical motion, and constant wake characteristics). His observations demonstrated perhaps the first obstacle-induced vortex street to be detected in the sea (Fig. 1). As Barkley pointed out, islands in clusters may act as a single obstacle to flow and extend wake effects far beyond that expected for the sum of the single islands. Also, a small change in speed or direction of the impinging current may affect not only the partitioning of energy in the system but also distributions of physical, chemical, and biological properties within island clusters and for hundreds of kilometers downstream.

Patzert (1970) fitted a complex model of flow (the Rankine vortex; Rouse 1963) to the observed structure of a frequent free-eddy phenomenon west of the islands of Hawaii, although the impinging flow and obstacle geometry there is correspondingly more complicated than in the Johnston Atoll case. In this instance the ocean responded to atmospheric forcing. Impingement of the trade winds on the profile of this high island group evidently created vortices or jets in the wind, which caused eddy formation in the water.

In a study of subsurface flow past island groups, White (1971a, 1971b, 1973a, 1973b) examined the wake of the Equatorial Undercurrent (or Cromwell Current) downstream from the Galapagos island group, which is comparable in scale to the Hawaiian island group. The unique position of the Galapagos, on the equator and obstructing an east-flowing current, suggested that the observed meanders in the flow constituted a barotropic Rossby wake, which differs from a von Kármán street in that it is time-independent and owes its existence to variations of the earth's rotation with latitude as well as to the presence of an obstacle and impinging current. Due to the usual vagaries of the impinging undercurrent, White could not distinguish between

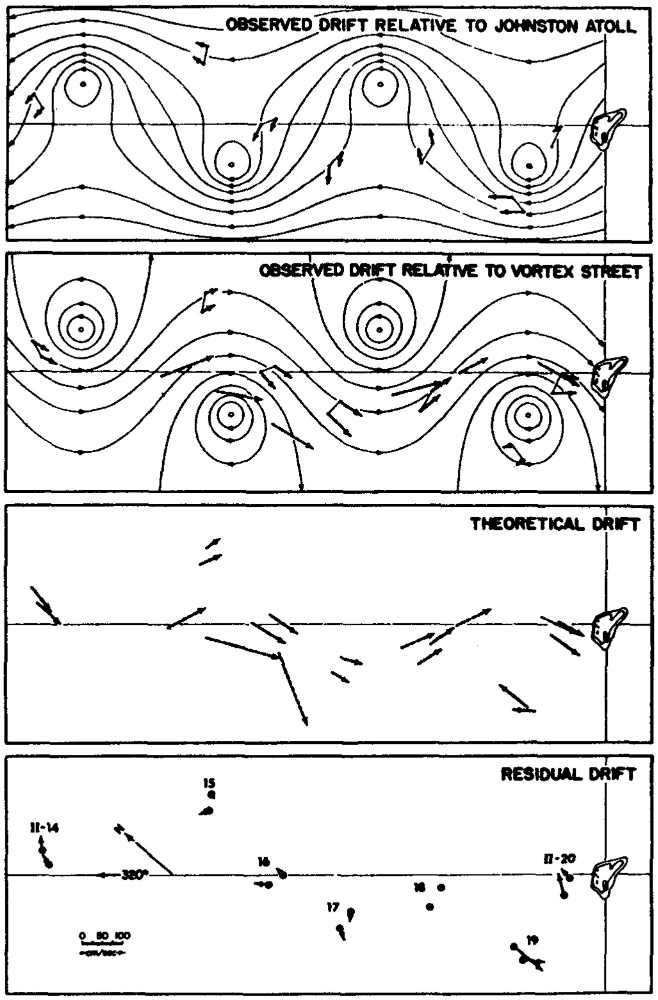


FIGURE 1. *Eddies in the wake of Johnston Atoll (Barkley 1972, fig. 3). Streamlines were derived from von Kármán vortex street model fitted to direct current measurements (arrows). Degree of success of the model is evident from comparison of the two lower panels.*

wake mechanisms. However, as the Rossby wake phenomenon requires an eastward flow, it is unlikely to occur in the flow past islands of the Californias (Baja California, Mexico and California, U.S.A.) because the impinging currents usually have no eastward component.

An obstacle is not a prerequisite for generation of surface eddies in the ocean. Barkley (1968) was able to account for a variety of observed flow patterns in the open-ocean boundary between the Kuroshio and Oyashio Currents by their resemblance to a type of flow consisting of two vortex streets lying side by side. In this instance, the vortices were apparently generated by the convergence of the two currents in the absence of fixed boundaries. That baroclinic eddies can be independent of islands, coasts, or strong current convergences has not been demonstrated, yet various studies confirm their commonplace occurrence in the open sea in general (*e.g.*, Bernstein and White 1974), and in the CCS in particular (Sverdrup and Fleming 1941, Wyllie 1966, Bernstein *et al.* 1977).

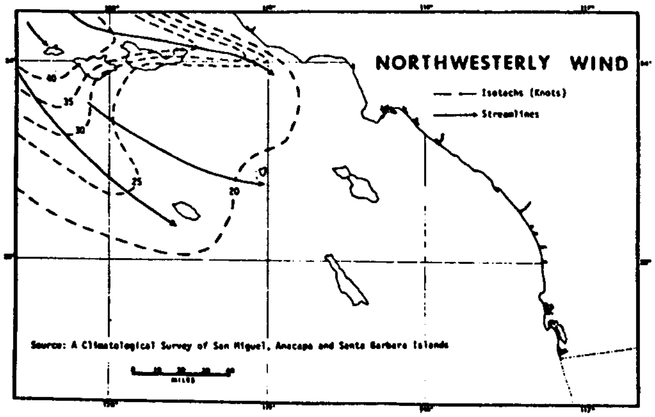
In the vicinity of island systems of the Californias, we must expect that a combination of effects of wind, current, and topography must be invoked to understand patterns of circulation (Pavlova 1966, Reid 1965). The flow impinging on the islands is as complex as island/bank

FIGURE 2. *Satellite photograph of sea-surface thermal patterns off California on 14 June 1975 (NOAA-3 satellite). Lighter shades represent cooler surfaces (Scripps Institution of Oceanography, Remote Sensing Facility).*

topography. Wind patterns exercise significant control, on the large scale, in producing the impinging flow and, on a local scale, in augmenting the perturbation of flow by the island and bank complex. Local winds are in turn affected by the islands and coastline. It is easy to understand why no simple theoretical treatment of the flow in this region can consistently account for observed current patterns downstream of the islands and banks of the Californias.

WIND

Wind stress on the sea surface is the primary source of the ocean's surface currents. The main theoretical approaches employed to account for the ocean's response to varying wind stress are those of Ekman (1905) and Sverdrup (1947), which, respectively, relate upper layer flow to temporal change in wind stress on the sea surface, and total water transport to spatial gradients of wind stress. These models have been applied to the California Current System. Bakun



Source: A Climatological Survey of San Miguel, Anacapa and Santa Barbara Islands

FIGURE 3. *Wind speed and direction over the SC Bight during northwest winds (U.S. Dept. Interior 1978, p. 65).*

(1973), for example, used Ekman's theory and computed upwelling intensity and timing regionally along the coastline of the Californias and farther north. These indices apply over distances too great to resolve localized phenomena. They may, however, be quite useful together with satellite thermal imagery in identifying regions and times of eddy activity associated with upwelling, should they prove to be commonplace. Sverdrup and Fleming (1941) found such eddies at the edge of an upwelling zone off Point Conception. Such an event appears again in a satellite photograph of thermal patterns in the sea off central California (Fig. 2). A cold plume and eddy extend seaward from a coastal upwelling zone, and the lower limb of a still larger eddy or meander is apparent—activity at least qualitatively similar to the upwelling edge-eddy found by Sverdrup and Fleming 42 years earlier off Point Conception.

Winds which affect local processes in the ocean off the Californias are predominantly out of the northwest and reach maximum velocity at a distance of about 200 km off the southern California coastline (Reid *et al.* 1958, Nelson 1977). Munk (1950), on the basis of his Sverdrup-based model of wind-driven circulation, found the offshore maximum in downcoast California winds to be consistent with the southward offshore flow and northward near-shore flow that seem to be prerequisites for strong SC Eddy development. Munk's meridional solution of the wind model also exhibits the weak and variable character of the main California Current.

In a more recent application of Sverdrup's theory, Nelson (1977) analyzed monthly mean values of wind stress in one-degree squares of latitude and longitude using surface wind observations from ships. This sampling grid was smaller (about 100 km) than those previously used for such wind studies, but still marginal for single eddy detection. His transport calculations from mean wind stress fields show flow directions consistent with the offshore equatorward transport of the California Current, near-shore poleward transport of the Countercurrent, and patterns south of Point Conception that are consistent with the SC Eddy.

The distribution of wind speed and direction over the region of the Channel Islands during northwest wind conditions is shown in Figure 3 (U.S. Dept. Interior 1978). It exhibits a two-jet system, consistent with wind retardation by the Northern Channel Islands of a single jet impinging from the north. High wind zones also are characteristic west and southwest off Point Conception (Reid *et al.* 1958, Allan Hancock Foundation 1965), but their role in eddy genesis is unassessed.

Sverdrup and Fleming (1941) discuss the possibility of coupling of atmospheric and oceanic eddies and raise the question of whether oceanic eddies are generated by the inherent ocean

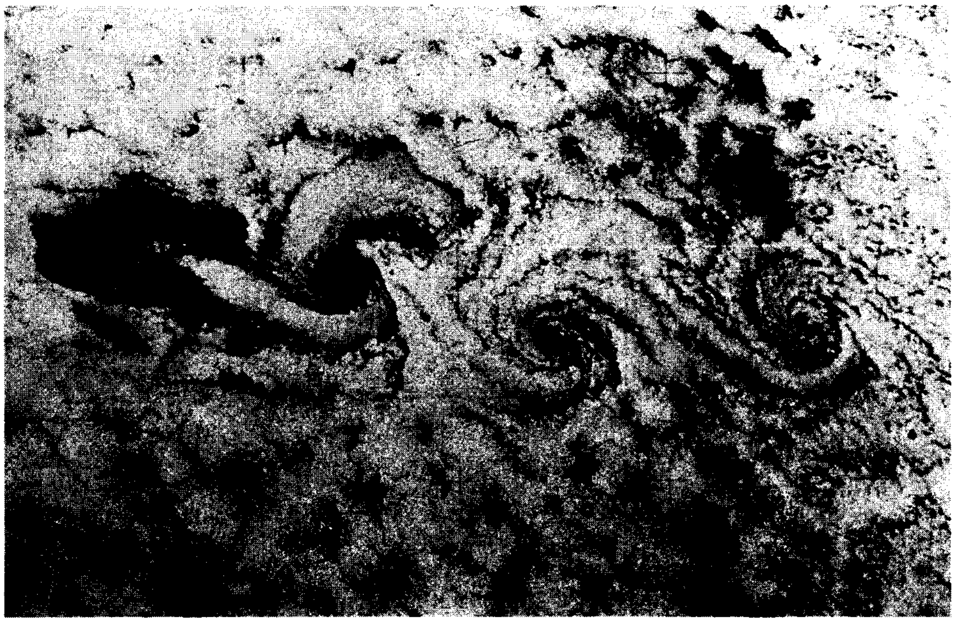


FIGURE 4. *Vortices in the atmospheric wake of Guadalupe Island off Baja California from Skylab on 6 September 1973 (NASA photograph SL-3* #121-2371).

current characteristics or are secondarily impressed on the ocean by the atmosphere. That this can happen elsewhere was shown by Patzert (1970), as noted above. Except for an eddy detected in the wind shadow of Cedros Island by Scripps Institution of Oceanography (SIO 1962), wind-induced ocean eddies have not been shown to occur in the CCS, although it is likely that they do occur.

Reports of atmospheric perturbations due to islands, and of von Kármán-like vortex wakes in particular, have been well documented in recent years. This is due, as Barkley (1972) notes, to "a special combination of circumstances: the wind, an obstacle, the right kind and quantity of cloud cover at the proper level, and a satellite overhead taking pictures; all must be present." Figure 4 is one such picture. Guadalupe Island is shown as seen from the orbiting Skylab satellite in September 1973. The cloud patterns clearly show a vortex street in the atmosphere downwind of the island. Such vortex wakes and other types of eddies are apt to be common in both ocean and atmosphere. Berger and Wille (1972) and Chopra (1973) review these phenomena and their dynamics. Additional examples of atmospheric flow perturbations by islands, and further discussion of their characteristics, are provided in Chopra's (1973) review of island effects on oceanic and atmospheric flow as known through 1970. Of obstacles in the CCS, only Guadalupe Island receives direct mention, but Chopra also reports effects of both smaller and larger islands which show that obstacles of virtually any size may produce systematic flow deviations. When the proper observations have been applied in the CCS, eddies are virtually always detected. Closer inspection of eddy systems may reveal that local coupling of atmosphere and ocean is responsible for the free eddies and meanders of the CCS as well as the previously established large-scale atmospheric coupling to which the main California Current owes its existence.

CALIFORNIA ISLAND AND BANK OBSTACLES

The islands and banks of the Californias are large enough relative to the impinging flow to induce or modify eddies of baroclinic scale. In full detail, the island/bank/basin topography of the Californias surpasses the complexity of most continental shelf systems of the world, leading Shepard and Emery (1941) to classify it as a "continental borderland," to distinguish it from ordinary continental shelves. The 100-m depth contour roughly describes a major break in the shelf slope (Emery 1958). At this depth, the northern group of Channel Islands (San Miguel, Santa Rosa, and Santa Cruz) may be considered a single obstacle to the flow, whereas the islands of the southern group (Santa Catalina, San Clemente, Santa Barbara, and San Nicolas) act individually. At the 500-m depth contour, the northern island group, San Nicolas, the Santa Rosa-Cortez Ridge, and Cortez and Tanner Banks act as a somewhat leaky, 200-km extension of the coastline north of Point Conception; as such, they would act on eddies the size of the SC Eddy. The direct effects of the California island and bank systems on flow have not been quantitatively specified in the literature.

It should be noted that islands and other obstacles to flow in the CCS can induce upwelling that is independent of wind. A theoretical treatment of eastern boundary currents by R. S. Arthur (1965) identified the importance of change of flow vorticity to upwelling in the boundary layer downstream of westward obstructions to southward flow in the CCS. Where the thermocline and nutricline are shallow, the result of such upwelling is cool, enriched water at the surface south of such promontories (Reid *et al.* 1958).

Examples of records exhibiting eddy patterns from direct current measurements near California islands are shown in Figure 5. Drogues released at 10-m depths were tracked in the Southern Channel Islands (Panel A). The circular trajectories shown were downstream of San Clemente and Santa Catalina Islands and depict eddies with diameters somewhat greater than 30 km and circuit times of about 3 days at 10 cm/sec. These eddies were probably caused by flow perturbation by the islands since the measurements were made under calm wind conditions (SIO 1962). On the other hand, the eddy defined by drogue trajectories near Cedros Island (Fig. 5, Panel B) was probably caused by wind forcing; northwest winds impinged on Cedros and Bahía Sebastián Vizcaíno during the measurement period. This 30-km eddy was located on the edge of the wind shadow of Cedros (labeled "calm area"), and may be the only documented case in the CCS of the wind's role in eddy genesis.

On a larger scale, eddies can be detected in the lee of the Channel Islands and banks during an offshore wind from thermal image patterns of the sea surface photographed by satellite (Fig. 6) the day before it photographed the patterns shown in Figure 2. The downstream eddy and meander patterns range from 30 to 100 km in diameter, and an eddy (< 30 km) appears near an upwelling zone off northern Baja California. Upwelling and eddy activity were apparent north of Point Conception, as well.

The effects of islands on flow as described for somewhat simpler systems elsewhere thus apply to the California Islands and associated banks, as well; they are capable of generating and shedding eddies of a variety of sizes. They may also alter the eddy patterns of the impinging flow by attenuating small eddies and deforming large ones.

EDDY PATTERNS OF THE CALIFORNIA CURRENT SYSTEM

It is likely that eddies, or eddy-like motion, impart to the flow of the California Current its characteristic large variability, in which excursions from the mean flow are at least as large as the mean flow itself. Flow is usually treated as the net motion resulting from superimposition of three main components: that due to, or balanced by, the internal distribution of mass (baroclinic mode); that due to wind stress on the sea surface, a barotropic mode under changing wind

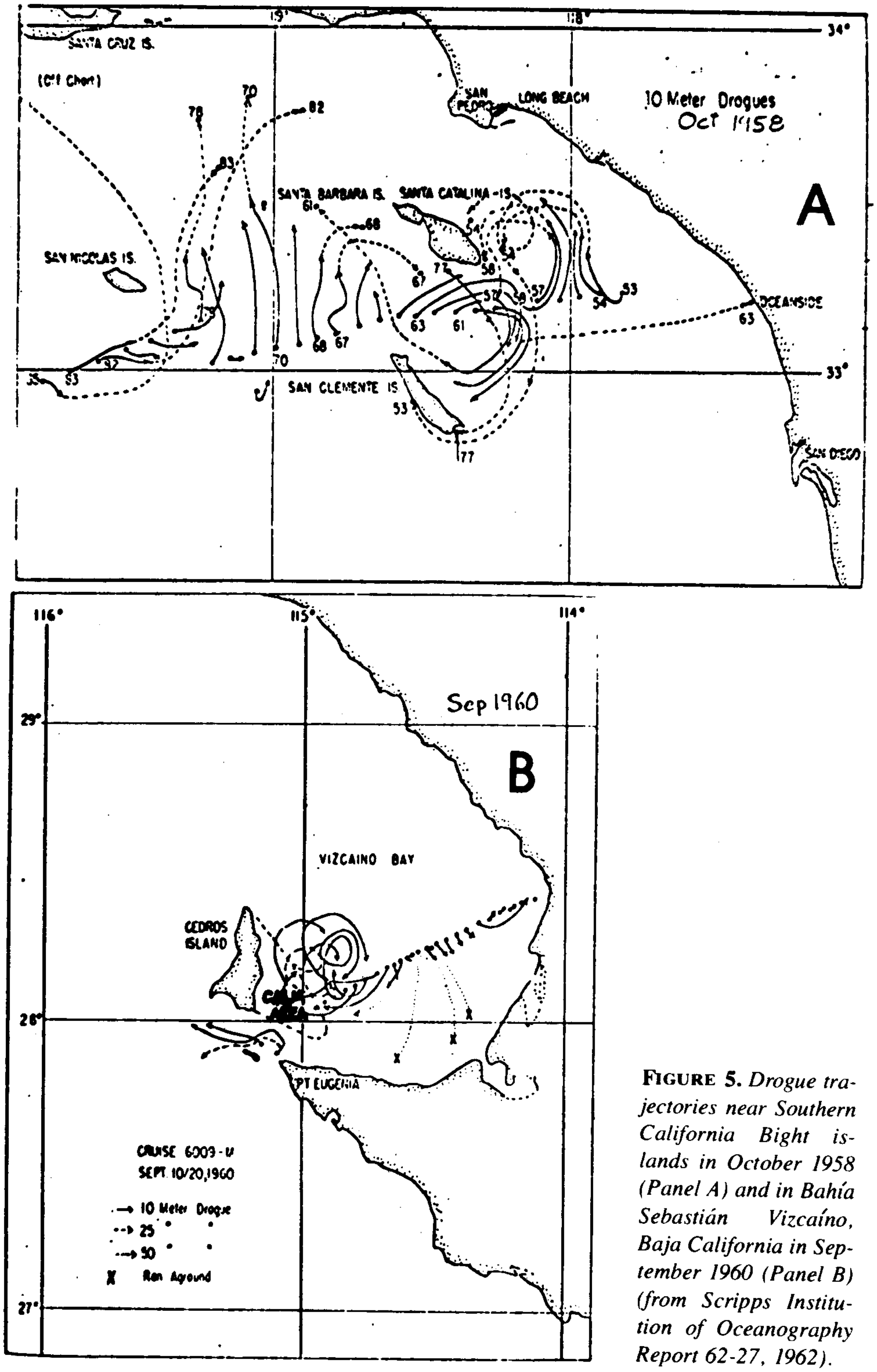


FIGURE 5. *Drogue trajectories near Southern California Bight islands in October 1958 (Panel A) and in Bahía Sebastián Vizcaíno, Baja California in September 1960 (Panel B) (from Scripps Institution of Oceanography Report 62-27, 1962).*

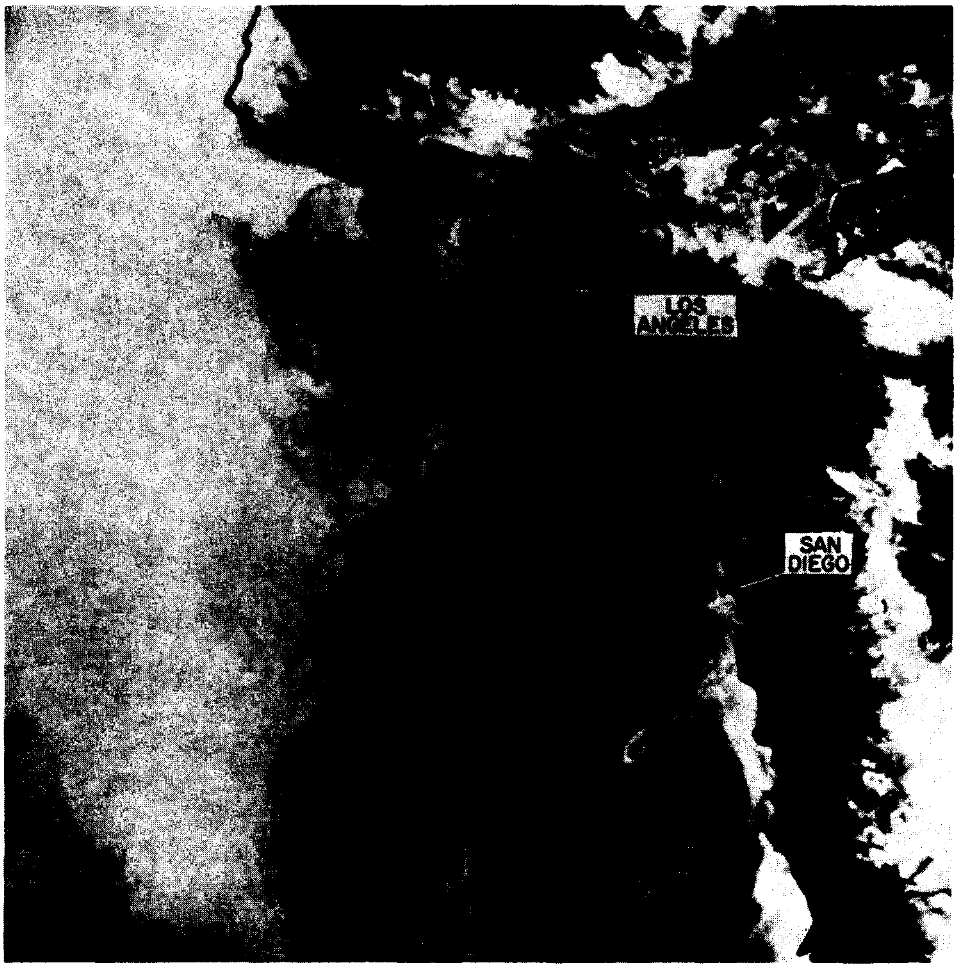


FIGURE 6. *Satellite photograph of sea-surface thermal patterns in the Southern California Bight on 19 September 1979 (NOAA-6 satellite). Lighter shades represent cooler surfaces (Scripps Institution of Oceanography, Remote Sensing Facility).*

conditions; and that due to tides and other cyclic internal motions, also barotropic. Direct determinations of currents are sensitive to all components, whereas currents depicted from the internal mass field (*i.e.*, from a spatial array of depth-integrated density profiles derived from temperature and salinity measurements) reflect only the mass-balanced baroclinic component of flow. Cyclical barotropic motions such as those due to tides or internal waves can, however, confuse interpretation of net motion using short-term direct current measurements. Internal wave displacements may also produce or suppress the appearance of small eddies in the baroclinic representation of flow (Knauss 1962). Local accelerations, *e.g.*, from storm activity, can cause poor estimates of flow velocity from the baroclinic representation.

Due to California Cooperative Oceanic Fisheries Investigations (CalCOFI) sample spacing (nominally a 30 to 60-km grid, at 30 to 90-day intervals), we can consistently identify baroclinic eddies larger than approximately 100 km in diameter and those persisting for more

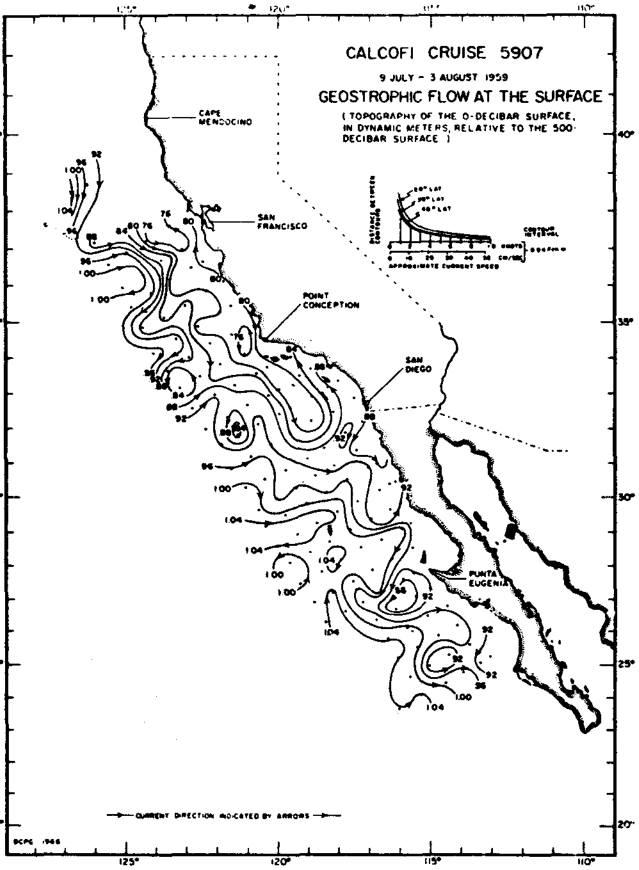
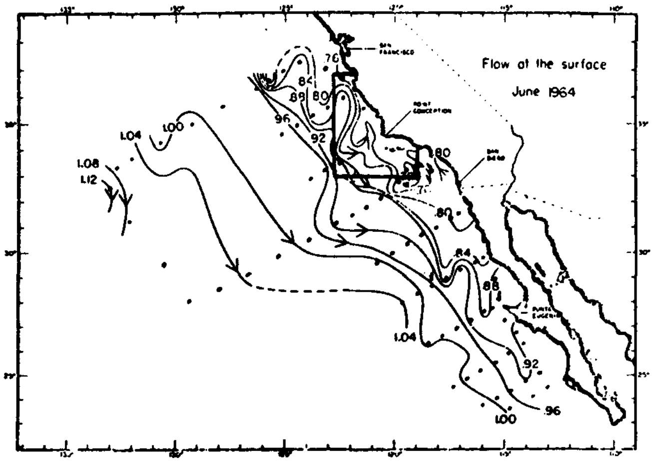


FIGURE 7. *Baroclinic representation of surface flow off the Californias in July 1959 (Wyllie 1966, p. 124). Eddies large enough to deform the density field and to be detected by the sampling grid (dots) appear as closed isobars; meanders appear as loops.*

than a month. We can resolve eddies 20 to 100 km in diameter, but at the risk of misidentifying them because of interference due to internal waves, meanders, error of measurement, and too few data points. Eddies of 20 to 100 km diameter and of less than one month's duration thus are known to exist, but their incidence and size distribution remain underestimated.

Relevant to this important range of eddy sizes is the work of Bernstein *et al.* (1977) on infrared imagery from the NOAA-3 satellite of thermal patterns in the California Current. Their work demonstrates the possibility of using thermal imagery for following eddy development and surveying their incidence, and confirms for a wide region what is observed in the field of mass and at current meter and drogue stations: most of the California Current is rich in eddies, including the flow impinging on the Channel Islands. A much more complete understanding of the distribution, persistence, and size of eddies can be anticipated from use of such satellite data to identify eddies upward of 20 km diameter and to document their genesis and decay.

Direct measurements of current speed and direction in the region off the Californias which are appropriate to eddy structure are made with difficulty and are not sufficiently numerous to support general conclusions on eddy incidence. Direct measurements made in the CCS by following parachute drogues (*e.g.*, SIO 1962) or by moored, recording current meters (*e.g.*, Lam 1972, Hendricks 1979) demonstrate flow variations consistent with effects of eddies of 10 to 50 km diameter which persist in deep and shallow waters for a few days to a few weeks. On the larger scale, baroclinic eddies from 100 to 1,000 km diameter and of months to years



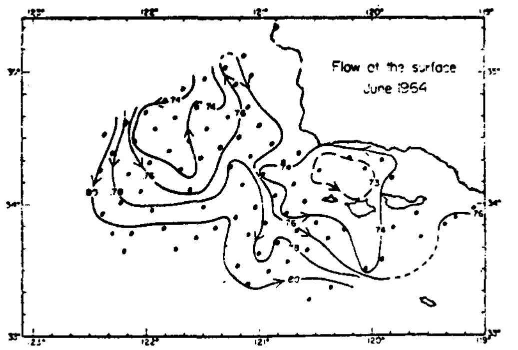


FIGURE 8. *Baroclinic surface flow as represented from the CalCOFI grid (top panel) and from an intensified grid (lower panel) in June 1964 (from Reid 1965, figs. 41, 42).*

duration are identifiable from the somewhat systematic coverage of the CCS region by surveys of the CalCOFI program. Tests of the hypothesis that flow in the CCS is balanced by the mass field have been conducted and the geostrophic method was shown to agree with various direct current measurements and to afford a somewhat better estimate of direction than of magnitude (Reid 1961, 1963, Reid and Schwartzlose 1962).

The geostrophic method also has been shown to apply in particular to eddy flow in the CCS. Baroclinic representation of an isolated eddy of about 80 km diameter was shown to agree well with drogue trajectories (Reid *et al.* 1963). This demonstrated the coherence of the velocity and mass fields and thus confirmed the adequacy of the baroclinic mode for representing eddy flow on the 100-km scale and for identifying smaller eddies, as well. Reid *et al.* (*op. cit.*) point out, perhaps as a cautionary note, that the particular eddy they describe would have "slipped through the mesh of the [CalCOFI] station grid" used for the geostrophic description had not a hydrographic station been added to the grid after discovery of the eddy by drogue work.

The incidence of baroclinic eddies and meanders in the main flow of the CCS and in the SC Bight is high. Virtually every chart of the baroclinic mode of flow given by Wyllie (1966) exhibits irregularities upstream of the island and bank system and in the CCS in general (Fig. 7). The California Current System, including flow impinging on islands, is probably rich in eddies smaller than 100 km, as well. Though some are known to be missed by the CalCOFI grid, small eddies nevertheless are often sampled and are common features in the baroclinic flow of the CCS (Wyllie 1966). Irregularities and eddies of small extent are apparent in charts of geostrophic flow off Point Conception for both January and June of 1964 (Fig. 8), periods when

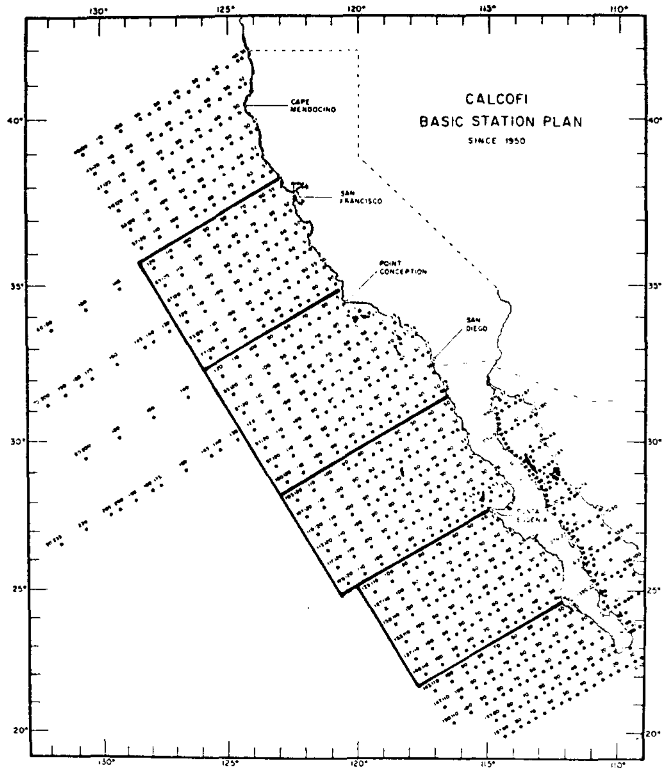


FIGURE 9. *Sectors of the CalCOFI grid used to enumerate baroclinic eddies of the California Current System. The sector containing the SC Bight covers 25 per cent more area than the others.*

the observation grid was augmented to give twice the resolution of the standard grid. As Reid (1965) notes, closer-spaced grids always seem to show proportionately smaller, but no less numerous, eddies.

Eddies in the California Current System, as defined by one or more closed streamlines of baroclinic flow, were enumerated from the charts of Wyllie (1966) by season in four size classes and four sectors off the Californias. I chose the sectors defined in Figure 9 to represent segments of the coastline between San Francisco Bay (38° N), Point Conception (35° N), Cabo Colnett (31° N), Punta Eugenia (28° N), and Bahía Magdalena (25° N). The sectors were covered, in part or totally, by 112 CalCOFI survey periods from 1949 to 1965. Separate counts were made of cyclonic and anticyclonic eddies because of their presumably different biological effects and modes of genesis. As a matter of convenience, eddy incidence is expressed as the mean number occurring in ten years, although the record used was 16 years in duration. Mean ten-year eddy incidences, corrected for gaps in coverage, are shown in Table 1. As noted above, the incidences of 20 to 100-km eddies are minimum estimates because at least some eddies of this size range were missed by the CalCOFI surveys. Larger eddies were missed when survey frequency was reduced.

Table 1 defines the level of eddy incidence in the CCS, demonstrating that eddies of all detectable sizes usually are present throughout the region off the Californias. It is also evident that there are times which show a low incidence of eddies of a given size or type. Eddy incidence demonstrates no significant seasonal variation except perhaps in the southernmost sector. Large eddies are rarer than small eddies in the Baja California sectors, but off California, eddies >200 km occur more often than those of 100 to 200 km diameter. In all areas and

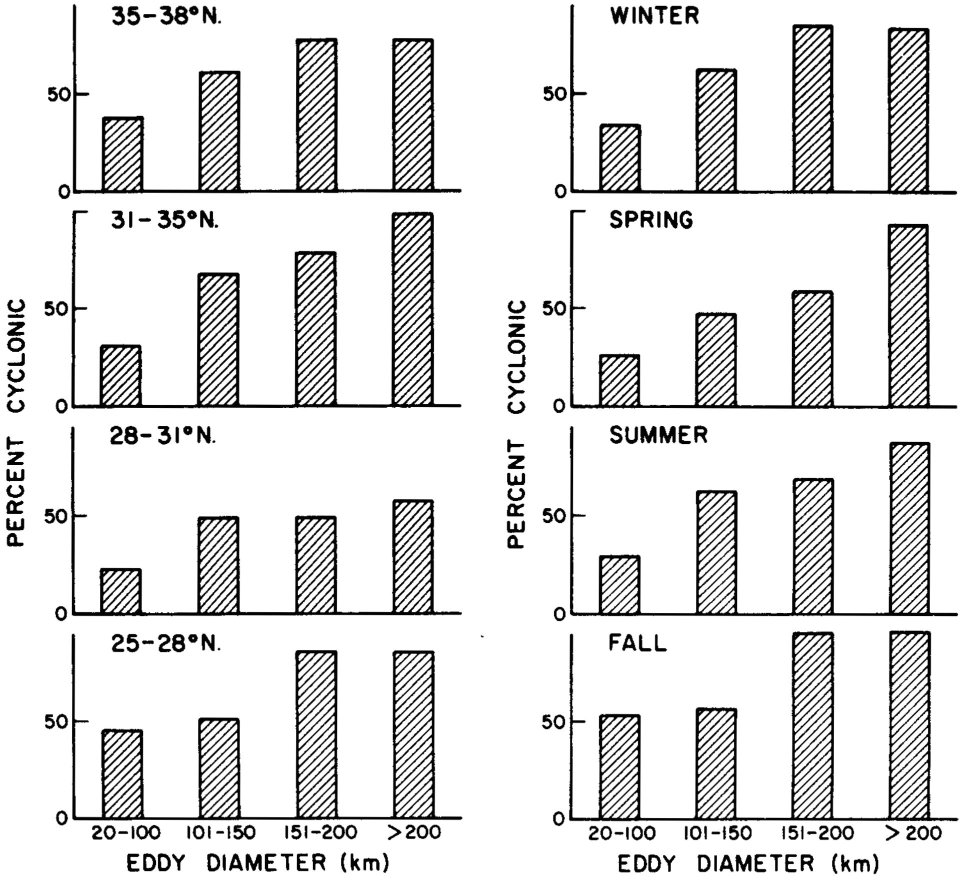


FIGURE 10. *Incidence of eddy type by size, sector, and season in the California Current System from Table 1. Panel A, by sector; Panel B, by season.*

seasons, eddies <100 km occur most frequently. In the sector containing the SC Bight, eddy incidence is dominated by the consistent (but not constant) presence of the SC Eddy. In this sector there is a corresponding paucity of both large anticyclonic eddies and small cyclonic eddies. The high incidence of small anticyclonic eddies in this sector, as well as in the two adjacent sectors, indicates that the small eddies could have been spawned by larger and more predominantly cyclonic eddies as a result of flow instabilities.

The dominance of cyclonic over anticyclonic eddies is seen in Figure 10 to occur progressively with increasing eddy size in each of the four sectors (Panel A) and in all four seasons (Panel B). The progression is most pronounced in the SC Bight (Panel A), due to the SC Eddy. This preponderance of cyclonic eddies may be ascribed to lateral friction augmented by planetary vorticity. Eddies created by lateral friction of the southward flow of the California Current against the coastal topography would be predominantly cyclonic due to inshore drag in the boundary zone. Perhaps more effective on smaller scales, the decrease in wind velocity between the coastline and the offshore maximum (discussed below) favors formation of cyclonic eddies. Wind stress gradients may be seen (charts 37 to 48 *in* Nelson 1977) to impart torque in the proper direction to favor cyclonic eddy formation in all months of the year in each

TABLE 1. Mean 10-year incidence of eddies by size, type, area, and season in the California Current System, 1949 - 1965, coast to 300 nautical miles offshore.

Eddy diameter (km)		20-100		101-150	
Eddy type*		a	c	a	c
Sector/season†					
	Winter	0.4	0.4	0.4	1.7
	Spring	2.8	0.9	1.3	1.3
35-38° N	Summer	3.6	2.3	0.9	1.9
	Fall	0.6	1.0	2.7	3.3
	Annual	7.4	4.6	5.3	8.2
	Per cent c	38.3		60.7	
	Winter	5.0	2.0	1.0	1.1
	Spring	3.7	2.3	0.2	1.3
31-35° N	Summer	6.2	1.9	0.3	1.6
	Fall	3.0	2.1	1.6	2.4
	Annual	17.9	8.3	3.1	6.4
	Per cent c	31.7		67.4	
	Winter	2.1	0.7	0.4	0.4
	Spring	4.1	1.5	2.8	2.4
28-31° N	Summer	3.1	0.6	1.4	1.7
	Fall	1.6	0.5	1.6	1.3
	Annual	10.9	3.3	6.2	5.8
	Per cent c	23.2		48.3	
	Winter	1.1	1.4	0.7	1.0
	Spring	3.2	0	1.8	0.5
25-28° N	Summer	4.0	2.2	1.8	2.1
	Fall	3.3	6.1	2.3	3.3
	Annual	11.6	9.7	6.6	6.9
	Per cent c	45.5		51.1	
All areas 25-38° N		47.8	25.9	21.2	27.3
	Per cent c	35.1		56.3	

* a = anticyclonic; c = cyclonic.

†Winter = January, February, March; spring = April, May, June; summer = July, August, September; fall = October, November, December.

151-200		>200		All sizes		Per cent c =
a	c	a	c	$\sum$ a	$\sum$ c	$100\frac{c}{a+c}$
0	1.9	2.4	3.7	3.2	7.7	
0.9	0.3	0	1.8	5.0	4.3	
0.9	0.9	0	2.0	5.4	7.0	
0	2.9	0.6	2.7	3.9	10.0	
1.8	6.0	3.0	10.2	17.5	29.0	
76.9		77.3				62.3
1.0	3.7	0	7.2	7.0	13.9	
0.9	2.6	0	6.4	4.9	12.7	
0	1.0	0.3	9.2	6.7	13.6	
0	0	0	7.3	4.6	11.9	
1.9	7.3	0.3	30.1	23.2	52.1	
79.3		99.0				69.2
1.1	0	1.5	1.2	5.1	2.3	
1.0	1.1	0.4	1.6	8.3	6.6	
2.0	2.2	1.4	0.6	7.9	5.1	
0.3	1.0	0	1.1	3.5	3.9	
4.4	4.3	3.3	4.5	24.8	17.9	
49.4		57.7				41.9
0	0.7	0.3	0.3	2.1	3.4	
0.7	0.9	0.3	0.3	6.0	1.7	
0.3	2.7	0.3	1.0	6.4	8.0	
0	2.0	0	3.8	5.6	15.2	
1.0	6.3	0.9	5.4	20.1	28.3	
86.3		85.7				58.5
9.1	23.9	7.5	50.2	85.6	127.3	
72.4		87.0				59.8

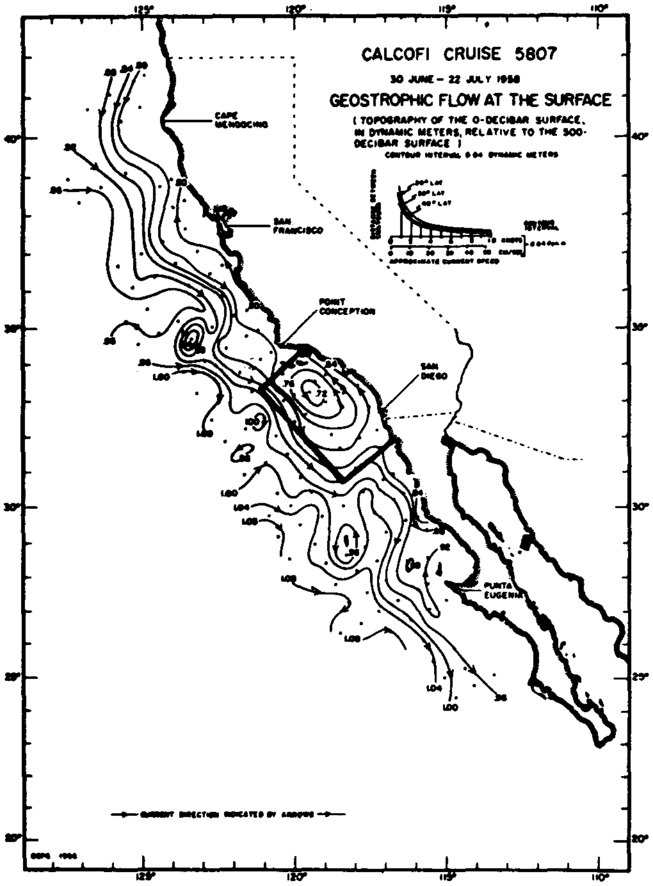


FIGURE 11. *Baroclinic representation of surface flow off the Californias in July 1958 (from Wyllie 1966, p. 111). The SC Eddy pattern (boxed) appears as a depression in the field of dynamic height anomaly.*

sector examined (Fig. 9), with the consistent exception of the southern half of the sector from 28° to 31° N off Baja California. This exception is important, as it helps explain the reduced incidence of cyclonic eddies in this one sector (Fig. 10, Panel A).

Finally, predominance of cyclonic over anticyclonic eddies is favored by their equatorial transport by the California Current due to conservation of angular momentum. Weak augmentation of cyclonic eddies and suppression of anticyclonic eddies occur by the Coriolis Effect (*cf.* von Arx 1962). With the exception of the SC Eddy, discussed below, the intensity (circulation strength) of eddies detected by CalCOFI surveys cannot be as well assessed as their incidence and type. This is due to the somewhat ephemeral nature of the eddies and to the inaccuracies of the geostrophic approximation of the baroclinic representation of flow. An intense eddy can thus appear weak in the charts analyzed, and *vice versa*.

SOUTHERN CALIFORNIA EDDY

The SC Eddy is the most resolvable of the eddies in the California Current System by virtue of its large scale and degree of permanence, which usually exceed the mesh and frequency of CalCOFI grid observations. Examples of eddies at least as large and intense as the SC Eddy are found in the main flow of the California Current (*e.g.*, Wyllie 1966), but have not been measured in further detail because of their transitory character.

One of the better examples given by Wyllie (1966) from the CalCOFI data is shown in Figure

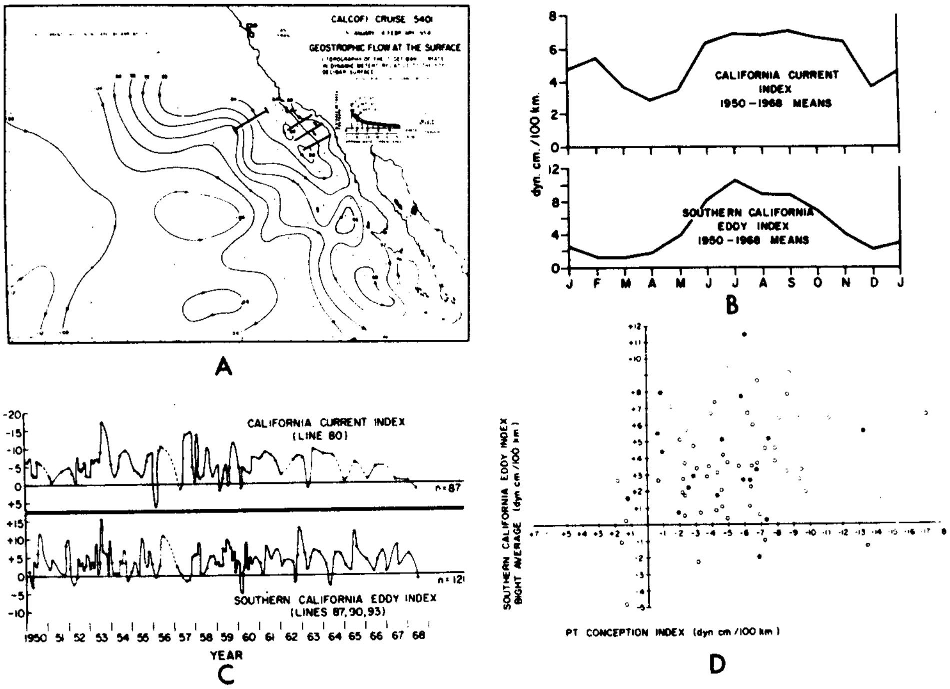


FIGURE 12. *Indices of baroclinic flow across sections (Panel A) off Point Conception (Panel B and C upper) and in the SC Eddy (Panel B and C lower), and the relationship between individual index pairs (Panel D). Indices derived from Wyllie (1966) by the author.*

11. The pattern of the SC Eddy (boxed) was augmented by the surfaced coastal countercurrent in this period (July 1958). Offshore, the eddy was augmented by a southwest-flowing, jet-like intensification of the California Current, which appears to have spawned two offshore eddies (one 200 km west of Point Conception and one centered near Guadalupe Island).

The SC Eddy, from Wyllie (1966) and Figure 12, Panel C, was present in every year (1949 to 1964) from July through January. From February through May, the time of the spring phytoplankton boom and the spawning of the northern anchovy (*Engraulis mordax*), the SC Eddy may periodically disappear for a month or more, flushing the surface waters of the SC Bight. Flushing is episodic in character, but most frequent in April (3 of 13 cases). The eddy may also "dissolve" in the baroclinic representation to an indeterminate field of weak flow. Such dissolution occurs in the same season as does flushing (again, 3 of 13 cases are in April). The eddy usually persists, however, in the absence of the surface countercurrent. This typically occurs in April to May, a period when the intensified California Current overrides the coastal countercurrent, to paraphrase Wyllie (1966). This pattern of events is supported by independent conclusions from drift bottle release and return statistics (Schwartzlose 1962, Squire 1977), and by the intensity of the SC Eddy, as I will now discuss.

The SC Eddy affords the best conditions for estimating changes in eddy flow intensity. Its stationary location and usual large size permit use of CalCOFI survey measurements to characterize two aspects of its flow: southward impinging flow off Point Conception, and the return flow of the inshore limb of the eddy. I computed indices of circulation strength from CalCOFI cruise measurements of the baroclinic slope of the sea surface (0/500 db; Wyllie 1966) across sections defined in Figure 12, Panel A. I chose these sections to show variations of strength of the California Current off Point Conception (northernmost section) and of the inshore limb of the SC Eddy and SC Countercurrent, when present (mean value of seaward slope across the three lower sections). Slopes shoreward of the index sections were not included in the eddy slope means to avoid effects of boundary instabilities associated with upwelling, nor were those off Point Conception to avoid including as well the effect of the Davidson Current, when present. The average annual cycle of flow past Point Conception in the period 1950 to 1968 (Fig. 12, Panel B, upper) is seen to be regular and to agree with the cycle and magnitude of circulation of the SC Eddy (Panel B, lower), which might be expected if the impinging flow drives the eddy, as noted by Pavlova (1966). The seasonal cycle of average surface flow impinging on the SC Bight (Panel B, upper) is in essential agreement with results of Reid (1965); offshore southward flow occurs all year off Point Conception and is strongest from May through November and weakest in spring. Circulation strength of the SC Eddy, as measured by flow of its inshore limb, is seen in Panel B to be greatest from June through October and least from December through April. Reid (1965) notes that the eddy's inshore limb develops to such a degree that it rounds Point Conception from October through January, and then constitutes a coastal countercurrent. He also shows that the Northern Channel Islands usually experience seasonal reversals of current direction due to their inclusion in the eddy's inshore limb from July through February.

Examination of flow across these sections month by month and year by year adds a perspective of the effects of eddies and meanders on flow estimation and indicates a high frequency of eddies imbedded in the mean flow to and through the Channel Island system. The time sequence of individual flow estimates, shown in Panel C of Figure 12, reveals a degree of variation in both incident and eddy flow intensity which is not apparent in the plots of averaged flow values of Panel B. This is because transient baroclinic-scale eddies and meanders detected in the flow are suppressed upon averaging. The fluctuations of individual indices in Panel C are caused by perturbations large enough to affect the field of mass, since the flow estimates were derived from the distribution of mass. Eddies or meanders of less than about 10 km radius (of curvature) or 5 days duration are unlikely to produce a detectable change in the mass field. The plots of Figure 12, therefore, reflect the abundance of eddies exceeding these dimensions.

Owing in part to the effects of eddies and meanders *not* reflected in the indices, it is difficult to predict flow intensity at a particular time and to specify the particular response of the SC Eddy to changes in impinging flow intensity. This is shown by the scatter of data points in Panel D of Figure 12.

PACIFIC EDDY COMPARISONS

It is of interest to compare SC Eddy characteristics with those of large eddies elsewhere in the Pacific, some of which have been investigated more intensively. A documented example of baroclinic doming and upwelling is provided by the Costa Rica Dome, produced by a major northward deflection of the North Equatorial Countercurrent as it impinges on the American continent (Wyrtki 1964). The dome is located in the bight of this deflection in a region where nutrients and thermocline both are close to the photic depth (Brandhorst 1958, Thomas 1970, Owen and Zeitzschel 1970a). Its physical characteristics denote a stationary, cyclonic eddy large enough to demonstrate nutrient enrichment effects (Brandhorst 1958, Broenkow 1965, Thomas 1970, 1977) and the responses of phytoplankton, zooplankton, and small nekton stocks (Blackburn *et al.* 1970, Owen and Zeitzschel 1970b, and references above).

A contrasting case is provided by the Hawaii Eddy phenomenon described previously. Despite the large vertical displacement (50 to 150 m) of the thermocline that is attributable to doming by the eddy (Patzert 1970), nutrient-rich waters lie deep. For enrichment of the photic zone to occur, water deeper than about 300 m would have to be raised more than 200 m to reach the bottom of the photic zone. McGary (1955) consequently found no evidence for photic zone enrichment that could be attributed to the Hawaii Eddy. Other significant biological processes are, however, evidently affected by the Hawaii Eddy; Sette (1955) describes evidence for the effect of the eddy on local fish populations.

Uda and Ishino (1958) have identified patterns of enrichment resulting from eddy systems off Japan comparable in scale and persistence to those off the Californias and Costa Rica. Areas of high concentrations of commercially and ecologically important fish, squid, whales, plankton, and benthic fauna were found to coincide with areas of high eddy activity, both near and far from land boundaries. Uda and Ishino distinguished between topographical eddy systems (those affected by topography) and dynamic eddy systems (those affected by current "collision").

Table 2 gives estimated magnitudes of various properties of the SC Eddy, together with reported magnitudes of California coastal upwelling and of other large eddy systems in the Pacific. As may be seen in the geostrophic flow atlas (Wyllie 1966), the SC Eddy may deviate from Table 2 values of size and circulation strength. This is caused in part by change in the obstacle profile confronting the current when changes occur in either the direction or depth span of the impinging flow.

Several comparisons of magnitude estimates in Table 2 are worth comment. Despite the varying eddy sizes, intensities, and vertical velocities, transport by upwelling is of the same order of magnitude in the SC Eddy, Hawaii Eddy, Costa Rica Dome, and in a segment of the coastal upwelling domain 200 km in length (the same distance along the California coast usually subtended by the SC Eddy). As may be seen from ambient nutricline and photic depths, nutrients are readily available for transfer up through the photic zone in all areas considered, except off Hawaii. The degree of enrichment and subsequent productivity of the SC Eddy is probably comparable, therefore, to that of other major eddy systems. The SC Eddy appears only slightly less effective in total transport of nutrients into the photic zone than does upwelling along a comparable length of the California coastline, although SC Eddy nutrients are transported into about three times the volume. Such ecological impact is enhanced by the role of the SC Eddy as an oceanic reservoir for washout of coastal and upwelling products from the Southern California Bight, as well as from Point Conception and farther north.

ECOLOGICAL EFFECTS OF THE SOUTHERN CALIFORNIA EDDY

Several biological effects of the SC Eddy have been identified in studies of phytoplankton concentrations and communities, zooplankton, and fish populations. Allen (1945) examined vernal distribution of diatom populations and abundances in the upper 60 m over the SC Bight in relation to baroclinic flow and bathymetry. The area of the Santa Rosa-Cortez Ridge system above 200 m depth is treated as an obstacle. Allen indicates local topographic control of both current patterns and of diatom abundance on a relatively intensified sampling grid (25-km spacing, six cruises in three months). He presents spatial variations of diatom concentrations ranging over five orders of magnitude in patterns which support his hypothesis that higher diatom concentrations occur off the Santa Rosa-Cortez Ridge axis, partly due to washdown of coastal upwelling from the north. The ridge axis usually defines that of the SC Eddy.

Sargent and Walker (1948), from a similar data set, examined patterns of abundance of several diatom populations sampled in the upper 60 m in and beyond the SC Bight. They considered these populations to be closely associated with what they treated as "cyclonic eddies of freshly upwelled water entering the area of observation from the north" (off Point Conception), which appear identical in size and persistence to the SC Eddy. Greater abundance of

TABLE 2. Parameters of Pacific eddies and California coastal upwelling.

	Southern California Eddy[1]	Johnson Atoll[2]	Hawaii Eddy[3]	Costa Rica Dome[4]	Small CCS Eddy[5]	California coastal upwelling[6]
Obstacle diameter (km)	200	26	100 (wind) 300 (current)	—	—	200 (length†)
Eddy type	stationary, topographic-dynamic	vortex street	wind-forced	free, stationary	free, stationary	(edge eddies)
Ambient* or incident flow (cm/sec)	20	60	30	55	20	20
Eddy flow (cm/sec) at 1/2 radius	30	80	50	40	20	—
Radius (km)	100	30	65	200	40	—
Decay time (days to 1/e)	100	16	>65	—	>14	14
Vertical velocity (m/day)	0.3	—	0.8 (initial)	0.1	—	1.0
Upwelling volume (m^3/day)	10^{10}	—	10^{10}	10^{10}	—	10^{10}†
Pycnocline elevation $\left(\frac{\text{ambient-dome}}{\text{ambient}}\right)$	0.3-0.5	—	0.4	0.7	0.1	0.4-0.6
Ambient* photic depth (m)	60	100	100	70	70	60
Ambient* nutricline depth (m)	30-70	75	300	40	40	20-60

Sources: [1] McEwen 1948; Wyllie 1966; Wyllie and Lynn 1971; Owen 1974.

[2] Barkley 1972; Frederick 1970.

[3] Patzert 1970; McGary 1955; Frederick 1970.

[4] Wyrtki 1964; Broenkow 1965; Bennett 1963; Owen and Zeitzschel 1970a.

[5] Reid *et al.* 1963; Owen and Sanchez 1974.

[6] Bakun 1973; Walsh *et al.* 1974; McEwen 1948; Wyllie and Lynn 1971; Arthur 1965; Sverdrup and Fleming 1941; Owen and Sanchez 1974.

* "Ambient" refers to condition in absence of phenomenon.

† 200-km coastal strip 50 km wide for comparison with SC Eddy.

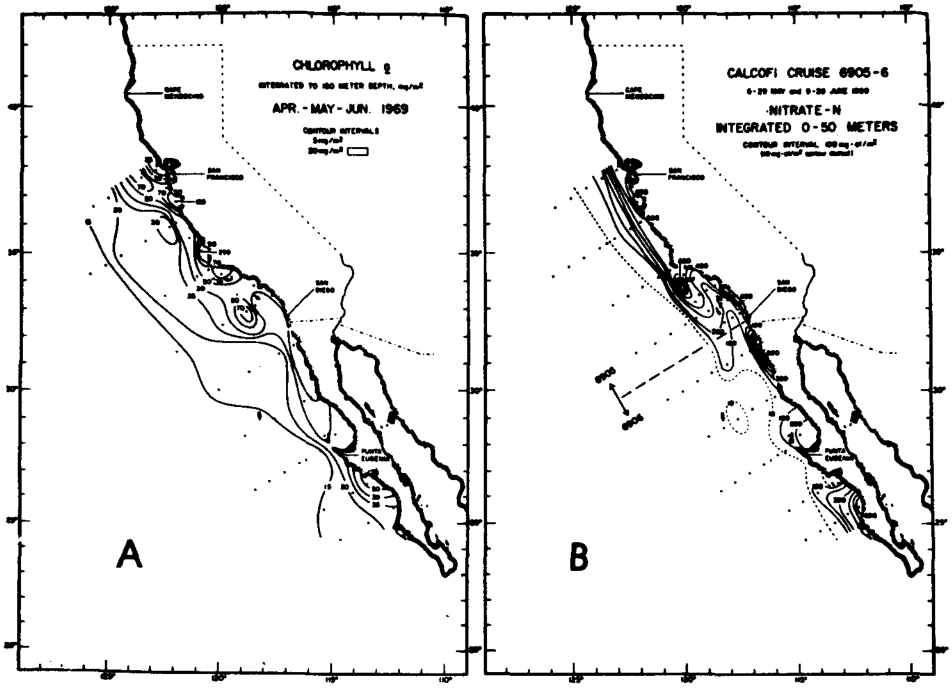


Figure 13. *Total chlorophyll* a *(mg/m²) to 150 m depth (Panel A, Owen 1974, p. 107) and total nitrate-nitrogen to 50 m depth (Panel B, Thomas and Seibert 1974, p. 37) off the Californias in spring 1969.*

several diatom populations in the offshore limb of the eddy was attributed to entraining of upwelled water north of Point Conception. Diminished abundances in the inshore limb were ascribed to nutrient depletion and grazing as the phytoplankton circuited the eddy. Change in phytoplankton community composition was also detected as the populations circuited the eddy, consistent with Allen's (1945) distinction between diatom communities inshore and seaward of the Santa Rosa-Cortez Ridge.

Spatial variation of community structure and of population densities is enhanced by the SC Eddy. Succession of community composition occurs along flow streamlines; where such streamlines are closed, as in the SC Eddy, successive communities are inevitably juxtaposed. This is apparent from the work cited above, which suggests a change in time and space from a diatom species ensemble characteristic of recent coastal upwelling to an ensemble characteristic of older surface-layer waters. Due to the SC Eddy, these ensembles were spatially juxtaposed in what may prove to be a characteristic state. This state demonstrates (perhaps more crudely than actually occurs) the creation of community patchiness by stirring, as defined by Eckart (1948), and is not necessarily confined to the phytoplankton alone.

Patterns of high phytoplankton concentration which correspond to those of the SC Eddy are shown by Owen (1974) and by Owen and Sanchez (1974) in terms of surface and depth-integrated chlorophyll *a* concentrations (Fig. 13, Panel A). These corresponded with patterns of surface-layer nutrient distribution of Thomas and Seibert (1974) at times when the SC Eddy was fully developed (Panel B). Together with the evidence for high persistence of the SC Eddy, these studies confirm that the effects observed by Allen and by Sargent and Walker are characteristic (rather than episodic) in the SC Bight. Primary production measurements in the SC Bight are too sparse to demonstrate an enrichment effect of the SC Eddy. A single transect of such measurements across the SC Bight (Owen 1974) showed primary production to be about six times greater in the SC Eddy than beyond it.

Brinton (1976) studied the population biology of *Euphausia pacifica*, the dominant species among the larger zooplankton of the SC Bight. He identified the SC Eddy and its associated upwelling regimes as a productive refuge for an identifiable population of the species.

Benthic-dwelling organisms with planktonic life history stages (usually larval) depend for population maintenance on being deposited, at the end of their planktonic stage, in waters shoal enough to permit their survival on the sea bottom. Off the Californias, where flow frequently diverges from the coast, such populations must depend on eddies and meanders in the mean flow to return a sufficient number of their meroplankton to the habitat. Although the SC Eddy is not cited in particular, examples include populations of the spiny lobster, *Panulirus interruptus* (Johnson 1960), and the red crab, *Pleuroncodes planipes* (Longhurst 1968). Both organisms spend extended periods as plankton in their early life history.

During spawning in the 1941 season, a population of the now decimated California sardine (*Sardinops caerulea*) was shown from plankton surveys (Sette and Ahlstrom 1948) to have concentrated its eggs and larvae in an area corresponding closely to that of the SC Eddy and its elevated diatom densities (Sargent and Walker 1948). Figure 14 shows this striking local correspondence, which suggests the possible sensitivity of the sardine stock to the SC Eddy. The surveys did not cover the entire range of spawning, however, and it is possible that other eddies beyond the SC Bight may have supported undetected spawning areas.

Since the replacement of the California sardine stocks by those of the northern anchovy (*Engraulis mordax*), CalCOFI plankton surveys have covered the spawning time and area of the anchovy. These have revealed (Smith 1978) that the region inclusive of the SC Eddy, comprising about 12 per cent of the spawning area of the anchovy's central subpopulation, contained, on the average, 48 per cent of the spawned larvae during the period 1951 to 1975; since 1966 this region has contained 64 per cent.

Berner (1959), in his study of food of anchovy larvae, noted that areas where larvae were found to be actively feeding corresponded to those of the copepod nauplii maximum, as described by D. K. Arthur (1956). Comparison of areas of active larval feeding in the SC Bight with corresponding charts of baroclinic flow (Wyllie 1966) shows that the area of feeding larvae corresponded with the inshore limb of the SC Eddy, although D.K. Arthur (1977) subsequently showed that the copepod nauplii maximum may also lie on the SC Eddy axis or in its offshore limb.

SUMMARY

Owing to the rapid attenuation of sunlight with water depth, over half of the total primary production of food in the offshore CCS occurs in the surface mixed layer, 10 to 60 m deep. The primary supply of inorganic nutrients to the mixed layer is from below. Lateral transport in the mixed layer imports virtually no inorganic nutrients, except directly from coastal upwelling zones, because the phytoplankton communities of the northeastern Pacific can strip the mixed layer of extant nutrients in only a few days. Local regeneration of nutrients from mixed-layer organics is known to be a nutrient source for sustaining phytoplankton growth under otherwise impoverished conditions, but has not been proposed to sustain the higher levels of production characteristic of the CCS off California. Southward transport of the California Current imports nutrients at depth and, at the same time, creates the shoreward upslope of the thermocline layer that makes possible enrichment of the mixed layer and photic zone. Actual transfer of nutrients

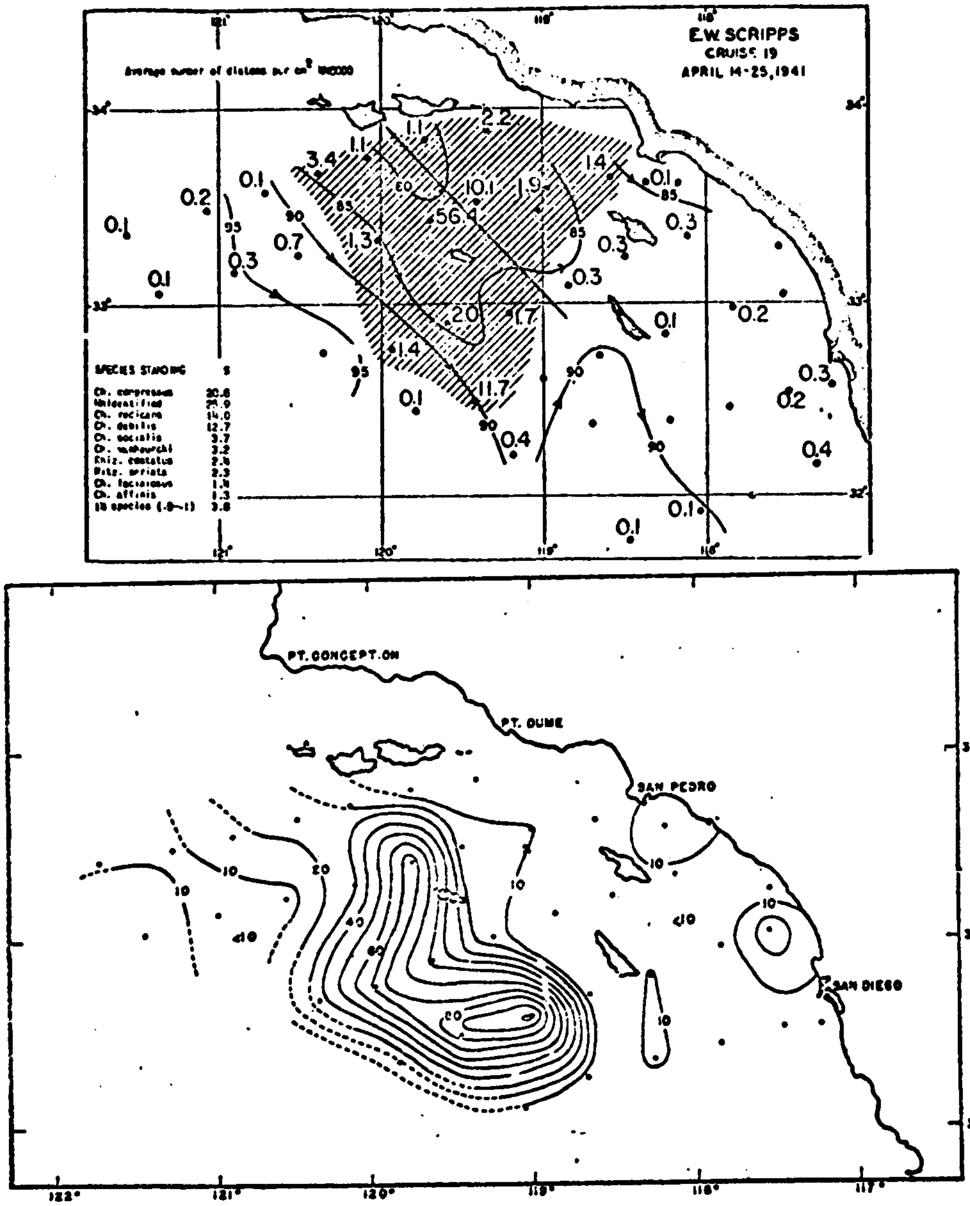


FIGURE 14. *(top) Distribution of diatoms and baroclinic flow in April 1941. Hatching denotes area of higher diatom abundance. Per cent contribution to total diatoms given beside each sampling location (Sargent and Walker 1948, fig. 1). (***bottom***) Distribution and concentration of sardine eggs over the spring 1941 spawning season. Values on isopleths are number of eggs under 10 m*^{2} *of sea surface (Sette and Ahlstrom 1948, fig. 4).*

to the mixed layer at high rates is episodic. The best known episodic fertilization process is wind-driven coastal upwelling; direct effects of strong upwelling are detectable to 50 km offshore, farther off capes, and perhaps farther yet if edge-eddies transport large, cold volumes offshore. The upward transport of nutrients in the SC Eddy can evidently approach that of the coastal upwelling strip. Although injected into a larger volume of water than in coastal upwelling, nutrient enrichment by the SC Eddy is continuous rather than episodic since the SC Eddy is a persistent feature of the region. Eddies of comparable enrichment potential are usually present elsewhere in the CCS, and small eddies are commonplace. Due to their transitory nature, they are difficult to study and their ecological impacts are thus undocumented. The cyclonic eddies of the CCS nevertheless are likely to be an important and variable determinant of the standing stocks, productivity, and community structure of life in the CCS, and particularly in the SC Bight.

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