

The Use Of Satellite Infrared Imagery for Describing Ocean Processes in Relation to Spawning of the Northern Anchovy (*Engraulis mordax*)

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Using satellite infrared thermal imagery in conjunction with extensive sampling for anchovy eggs and adults during March and April 1980, we were able to confirm that large areas of the coastal ocean off California were avoided by anchovies during the peak of spawning due to entrainment into the California Current of $\leq 14^{\circ}$ C water that upwelled north of Point Conception. Upwelling began coincident with the onset of winds from the north and proceeded in pulses separated by a few days. Plumes of upwelled water appeared to be advected southward in ladder-like rows by the California Current. A saline 50+-m-deep warm water pool, 40 km off Ensenada, Baja California, Mexico also was avoided by anchovies. The appearance of an inshore 16° C refuge and an extensive 220-km warm-water "wake" associated with Santa Catalina Island also were observed. Each of these oceanographic features was confirmed by ship observations.

Introduction

The recent acquisition of a satellite remote sensing facility at the Scripps Institution of Oceanography has permitted us to examine thermal imagery of the Pacific Ocean adjacent to the United States-Mexico west coast on a daily basis using the NOAA-6 polar orbiting satellite coincident with fine-grid oceanographic ship observations. Our objectives were to relate variations in mesoscale (approximately 200 km) sea surface temperature distributions with anchovy spawning and to identify and delineate important ocean

processes that might be important to the survival of fish eggs and larvae, e.g., upwelling (Lasker, 1978) and offshore transport (Parrish and MacCall, 1978).

During the period of the observations reported here, 14 March to 14 April 1980, a variety of dynamic oceanographic events were observed, including (1) the development of coastal upwelling plumes off Pt. Conception and Pt. Sur, California; (2) the entrainment of these cold-water plumes into the southward-flowing California Current; (3) the formation of an extensive "wake" associated with Santa Catalina Island; (4) the development of a

warm-water refuge in the Southern California Bight between Santa Catalina and the coast; and (5) the formation of sharp oceanic frontal boundaries. These are described in the following sections and discussed in relation to anchovy spawning, egg, and larva distribution, and larval survival.

Surveys are made each spring of recent anchovy spawning in order to estimate anchovy spawning biomass and include sampling of anchovy eggs, larvae, and adults as well as physical oceanographic measurements. During the spring of 1980, clear skies prevailed during the observational cruise of the R/V *David Starr Jordan*. Satellite infrared images were collected concurrently with ship observations.

Methods

Remote sensing

The Scripps Institution of Oceanography Remote Sensing Facility has a direct reception antenna and terminal, an information handling subsystem and an interactive digital image manipulation system. The facility can receive the analog AVHRR data directly from the NOAA-6 polar orbiting satellite and convert it to digital form. The data are then analyzed on a video display or stored on computer magnetic tape for further processing and analysis. Images for this study were collected from 14 March 1980 through 14 April 1980. The area studied extended from approximately Monterey Bay, California (37°N, 122°W) to Vizcaino Bay, Baja California, Mexico (28°N, 115°W) and out to sea about 400 n. mi. from shore. Within this region, particular attention was directed to the Southern California Bight area, approximately 32°N

to 34°30'N and 117°W to 121°W. NOAA-6 satellite passes were collected daily or twice a day. For daytime passes, clouds and atmospheric effects were seen using the NOAA-6 visible channel. For nighttime passes, clouds and atmospheric effects were evaluated on the basis of the time persistence of ocean features compared to the more rapidly changing atmosphere. The infrared data were enhanced to cover the full range of sea surface temperature sensed by the radiometer. Temperature calibration of each image was done by relating pixel gray-scale values to same-day sea surface temperature observations from ships at several locations. Computer programs for processing and analyzing the data were made available to us by the staff of the Scripps Remote Sensing Facility.

Shipboard observations

The National Oceanic and Atmospheric Administration research vessel *David Starr Jordan* recorded discrete surface temperatures at all stations with a bucket thermometer; salinities and temperature were continually monitored also with a thermosalinograph throughout the sampling area from San Francisco to central Baja California, out to approximately 200 n. mi. Oceanographic and biological sampling stations were occupied along the normal California Cooperative Oceanic Fisheries Investigations survey (CalCOFI) lines (Kramer et al., 1972) and at more closely spaced intervals in selected areas.

A vertical plankton tow of 1-min duration was taken from 70-m deep with a 0.333-mm mesh conical net of 25-cm diameter every 4 n. mi. along the grid to collect anchovy eggs (Stauffer and Picquelle, 1980). Nine-hundred and sixty-

one stations were sampled in water ranging from 11° to 17.5° C. Fifty-two hauls were taken with a midwater trawl to sample for adult anchovies in the upper mixed layer. The temperature relationship between spawning and temperature was investigated further by examining records of five March–April CalCOFI cruises from 1969 to 1979 for anchovy egg occurrence versus temperature.

Evaluation of the Northern California coastal upwelling plumes

The changing areal extent and southward progression of cold-water upwelled plumes were examined in a series of infrared images collected during the period of this investigation. Two images recorded nine days apart (19 March and 28 March) for the southern California Bight reproduced in Fig. 1, (a) and (b) respectively, illustrate the evolution of coastal upwelling plumes originating off Point Conception in late March 1980.

For the purpose of this study, the differences in gray tone are taken as indications of sea surface temperature changes. An increase in the extent and intensity of light tones relates to a decrease in sea surface temperature. Clearly evident are the upwelling pulses which developed north of Pt. Conception and which appear to become entrained as they intrude into the southward-moving California Current. One interpretation is that once formed each plume advanced southward carried by the California Current and retained its basic shape in ladder-like sequence (see also Fig. 4). Eventually these plumes of cold water merge and assume a southward-pointing tongue that does not significantly invade the Southern California Bight inshore of about 150 km. This large cold-water incursion with a

leading edge of 14.5–15.0° C was confirmed by shipboard surface temperatures, 27 March to 12 April (Fig. 2). Sea surface temperature isotherms derived from satellite imagery compare remarkably well with those from shipboard observations as shown at the bottom of Fig. 2. Salinities taken concurrently [see Fig. 3(a) and 3(b)] bore out the conclusion that cold water was upwelled near Pt. Conception and Pt. Sur since salinities inshore were high and isohalines were crowded around shoreline centers of cold water, a characteristic of upwelling (Reid et al., 1958).

Anchovy spawning in the Southern California Bight and cold-water intrusion from Northern California upwelling centers

Despite the “snapshot” nature of 6 April infrared imagery (Fig. 2) of the Southern California Bight, previous and subsequent photographs show clearly that the mesoscale features of surface temperature change slowly so that, for a given day, the temperature distribution does not appear to be markedly different from the preceding or following day. The slow-changing behavior of mesoscale thermal features off California was first described by Bernstein et al. (1977). Thus the biological sampling done over a few days can be compared to a single day's infrared image.

In this study, because thermal imagery was taken coincident with anchovy egg and adult sampling, it was possible to compare sea surface temperature with spawning incidence. Figure 4 is a thermal image from 6 April which has superimposed on it the geographic distribution of anchovy egg catch. The distribution of first-day anchovy eggs clearly showed that nearly all spawning was confined to the

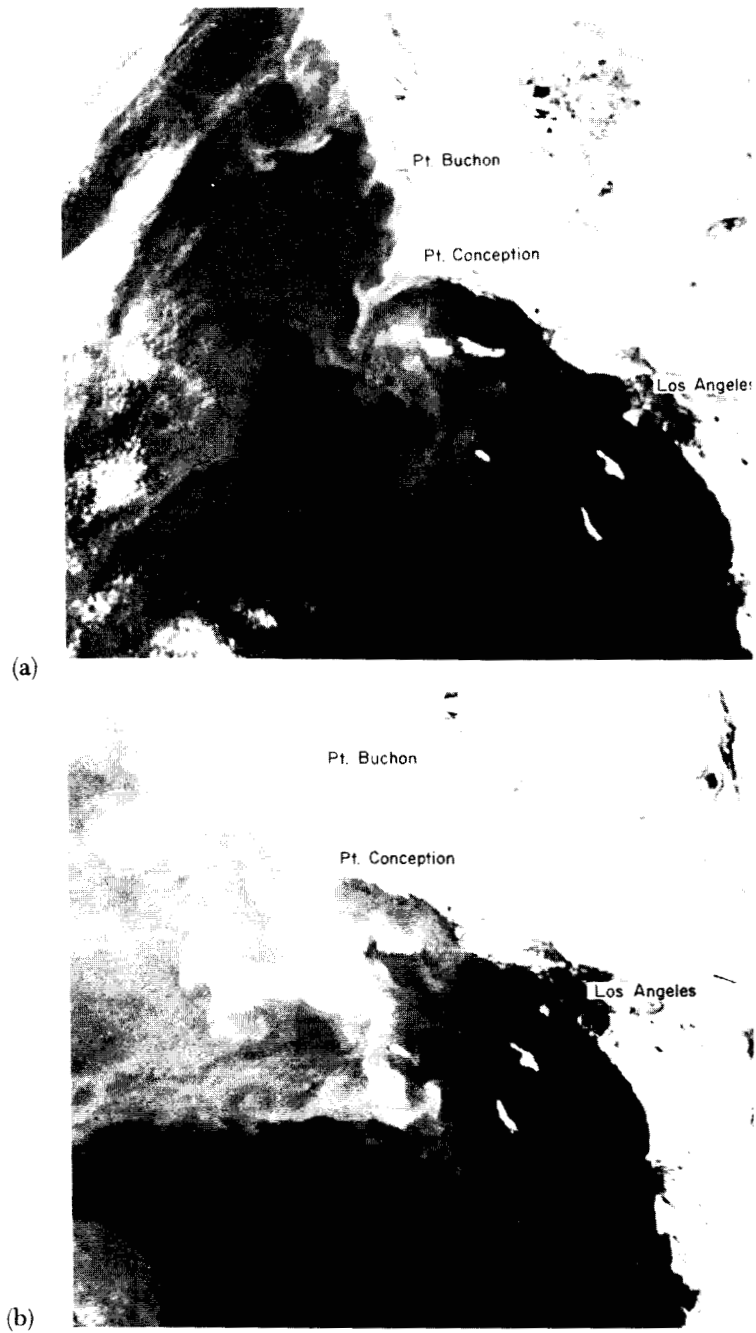
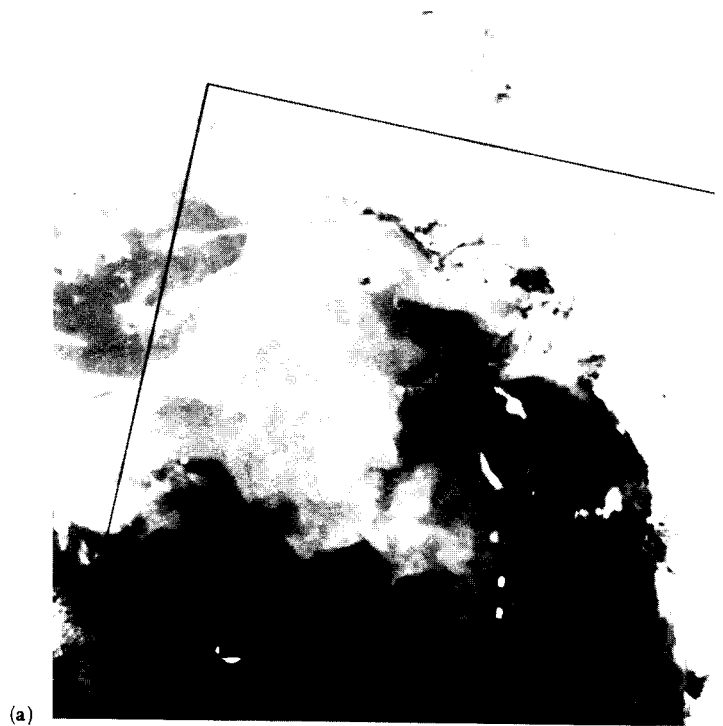
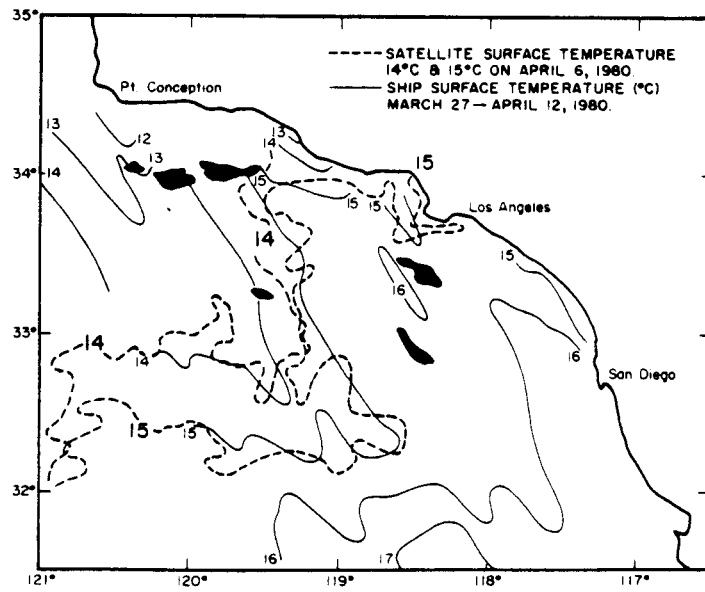


FIGURE 1. NOAA-6 infrared photographs from Pt. Sur, California to Ensenada, Baja California. (a) Upwelling began along the northern California coast about 14 March 1980 and was well established on 19 March when this photo was taken. (b) Nine days later cold water from upwelling was extensive and additional upwelling plumes established at and north of Pt. Conception. Warm-water wakes are seen from virtually all the islands in the Southern California Bight.



(a)



(b)

FIGURE 2. Match of satellite and ship sea surface temperatures. (a) 6 April 1980 NOAA-6 infrared photograph showing cold water extending south. (b) Match of 27 March to 12 April ship surface temperature observations with contoured gray-scale-derived temperatures (6 April 1980).

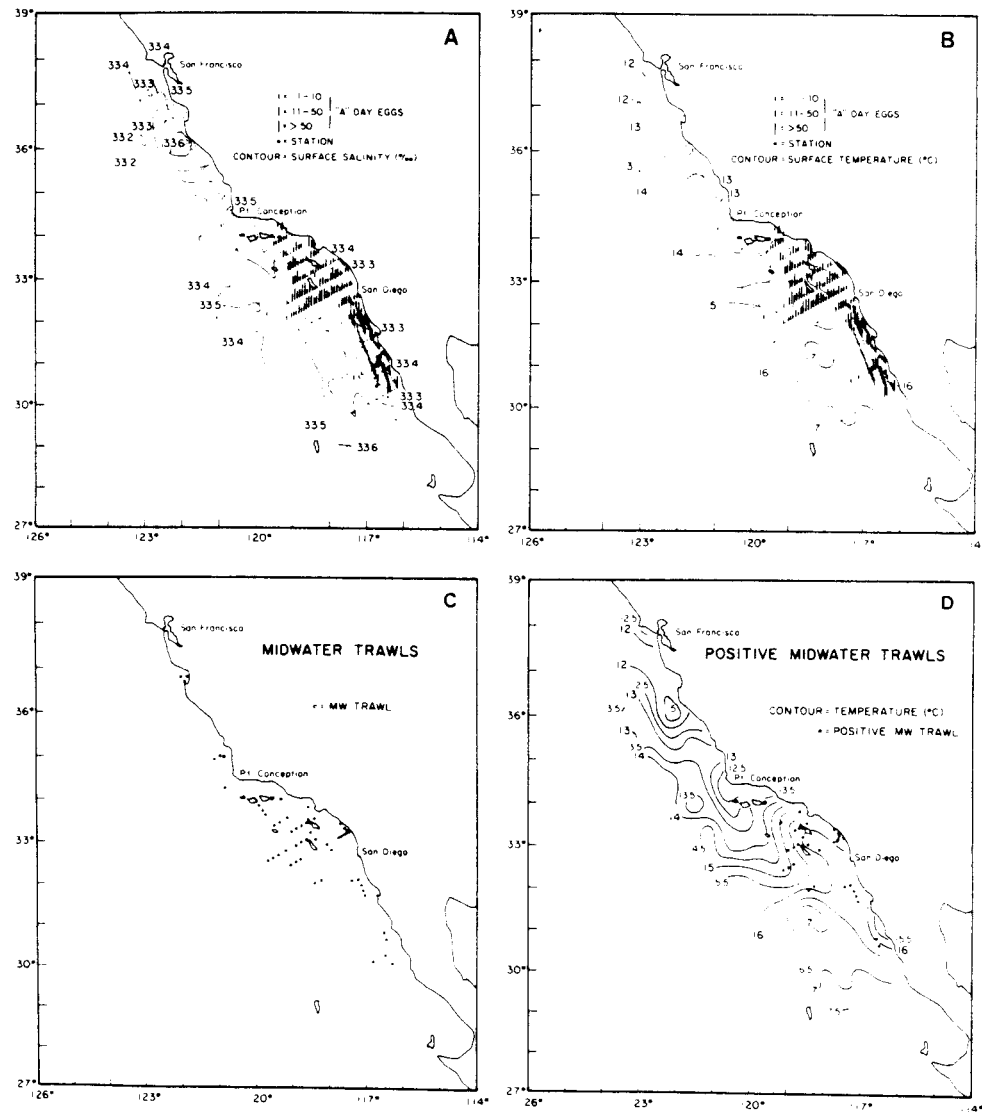


FIGURE 3. Distribution of anchovy eggs and adults in relation to salinity and temperature. (a) First day of spawning eggs and salinity. (b) First day of spawning eggs and surface temperature. (c) All midwater trawls taken from 27 March to 12 April 1980 by R/V *David Starr Jordan*. (d) Adult anchovy catches by midwater trawls and temperature distribution. Compare this with Figure 4(b).

Southern California Bight [Figs. 3(b) and 4]. The seaward extent of spawning was apparently abridged by the southward intrusion of recently upwelled water indicated by the 14°C isotherm. The series of infrared images examined showed that a large pool of warm water which had been prevalent prior to upwelling, was displaced by this southward flow. Thus during late March and early April 1980

there were two distinct temperature regimes in the general geographic region where anchovy spawning normally takes place. There was a cold area resulting from upwelling off Pt. Conception and north and a large warm area which extended from Baja California into the Southern California Bight and approximately 185 km offshore. An infrared image from 28 March of the California



FIGURE 4. Distribution of anchovy eggs superimposed on the thermal image of the Southern California Bight taken 6 April, 1980. The 14°C isotherm plotted from satellite gray-scale calibration has been drawn in. Feathery white objects are clouds. Squares indicate number of anchovy eggs under one square meter of sea surface.

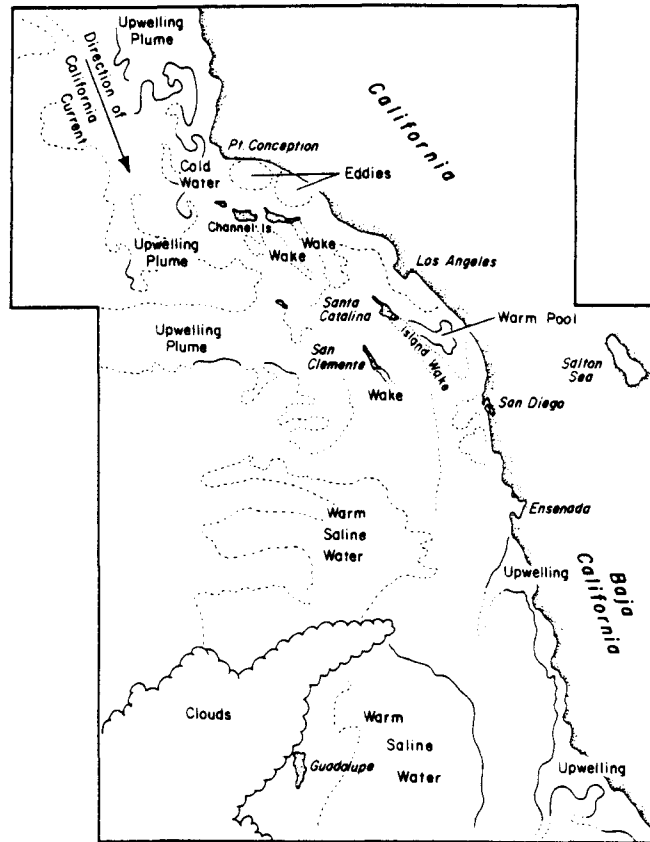


(a)

FIGURE 5. Infrared photograph from NOAA-6 showing California Current and Southern California Bight region, 28 March 1980. Note the sequential westward upwelling plumes descending from Pt. Conception. The large warm (17°C) saline ($33.5\text{--}33.6\text{‰}$) pool west of Ensenada and east of Guadalupe Island was an effective barrier to anchovies. The Southern California Bight had a temperature regime intermediate ($14.5\text{--}16^{\circ}\text{C}$) to the upwelled water moving south outside the Channel Islands and the warm saline pool off Baja California.

Current and the coast of California and Baja California, shown in Fig. 5(a), illustrates the features just described. In Fig. 5(b) is our interpretation of the image. The satellite temperature/anchovy egg findings are corroborated by mapping the distribution of first day eggs on sea surface temperature observations made concurrently aboard ship. The histograms in Fig. 6 show that anchovy did not enter water colder than 12.5°C nor warmer

than 17°C in March–April 1980. However, most of the stations where eggs were found were in water warmer than 14°C . This was unexpected since 14°C is the normal spawning temperature for the northern anchovy. Data from March–April 1969, 1972, 1975, 1978, and 1979 CalCOFI cruises are also shown in Fig. 6 (a). In earlier years appreciable spawning took place at temperatures above 16.5°C and in water colder than 14°C . The



(b)

FIGURE 5. continued.

modal temperature for anchovy spawning in March and April from 1969 to 1979 was 14–15° C, but was 15–17° C in March–April 1980.

In 1980, the determination of the age of each egg provided additional information on the drift of anchovy eggs and the integrity of the water masses in which they were spawned.¹ Figure 6 shows that each of 3 days' concurrent spawning throughout the spawning range of the anchovy were remarkably similar in tem-

¹Eggs were not staged as they were in 1980, thus 3 days of spawning are represented in the composite histogram of mean values (Fig. 6).

perature distribution. Our conclusion from this comparison is that transport or drift was not extensive for at least 3 days after spawning and that anchovy eggs stay with the water mass in which they are spawned. Thus despite the gradual day-to-day southward progression of the cold wedge of previously upwelled water by the California Current observed by satellite, warmer water outside the wedge remained intact. Thus eggs and larvae in warmer water were not subjected to colder temperatures since advective mixing was minimal judging from the satellite photographs. In fact, in the middle of this month-long period of satellite radiometer

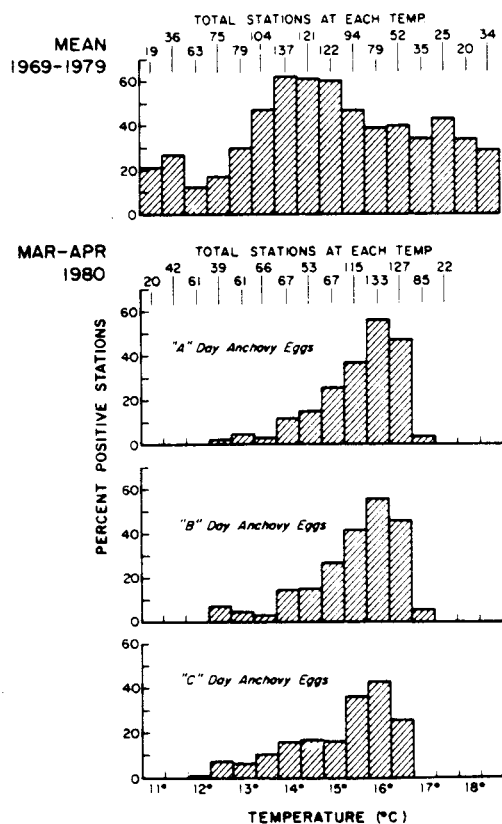


FIGURE 6. Percent of stations at different temperatures where anchovy eggs were found during March and April, the peak of the anchovy spawning season. (a) Average of 5 cruises (1969, 1972, 1975, 1978, and 1979). Note that modal temperature is 14–15° C; eggs were not staged. (b) Percentage of stations with anchovy eggs in 1980. A, day eggs are less than 24 hr old; B, eggs are between 24–48 hr old; C, eggs are from 48–72 hr old. Modal temperature in 1980 was 16° C.

observations, a storm swept through the area on 1 and 2 April, while ship sampling continued. Except for blurring of frontal temperature gradients, no major change in the surface thermal features could be seen.

Indicators of larval drift and exclusion of adults by upwelling

Relatively high numbers of anchovy larvae were found in plankton hauls

taken by the Russian vessel, R/V *Tikhookeanskiy*, in the coastal area north of Pt. Conception in February 1980. Temperatures were very warm for this entire zone in February; for example, 10-m temperatures off San Francisco were 13°–14° C, compared to 11–12° C found normally, with progressively warmer conditions to the south, i.e., 15° C for the line of stations off Pt. Conception. Winds were light and from the south prior to March 11 and upwelling was minimal, judging from average wind speed at Pt. Conception (Fig. 7). Winds from the north increased markedly on March 12 and persisted. When the area north of Pt. Conception where anchovy larvae had been collected in February, was sampled in March, no larvae of any age were found. This suggests that the extensive upwelling as indicated by wind data and observed by satellite carried anchovy larvae out of the coastal zone and into the California Current while at the same time adult anchovies were excluded as evidenced by lack of fish in trawls [Fig. 3(c) and (d)]. The start of upwelling on 14 March and the progressively colder temperatures appeared to have excluded anchovies from that time on. The leading edge of the cold-water mass generated 14 March by upwelling off Pt. Conception by 6 April travelled south approximately 300 km at a rate of about 12.5 km/day.

Exclusion of anchovies from a warm saline zone off Baja California

Satellite pictures (Fig. 5) reveal the large areal extent of a warm region of 17° C and warmer off Ensenada, Baja California. In previous years 17° C has been compatible with spawning (Fig. 6), but spawning in 1980, however, was restricted to a band 40-km wide, parallel to the Baja California coast avoiding this

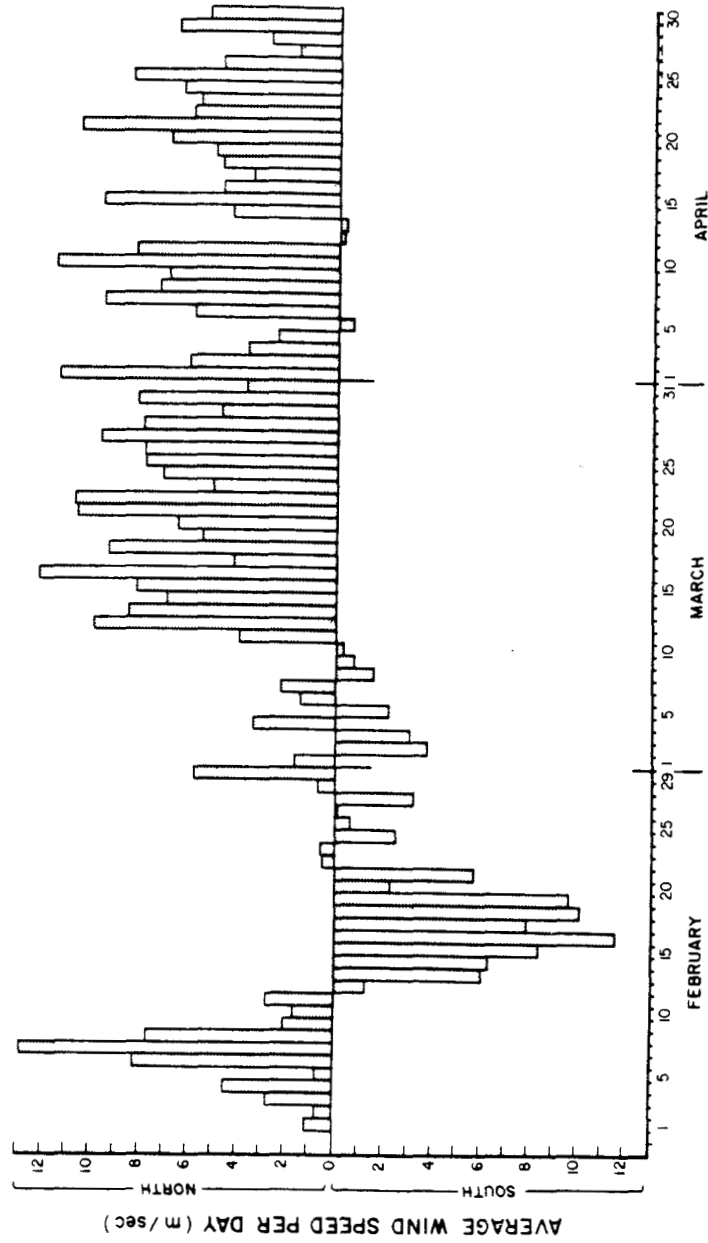


FIGURE 7. Average windspeed per day at Pt. Conception, California, February-April 1980. Upwelling was first observed by satellite at Pt. Conception on 14 March (see Fig. 2) and after sustained southward winds began. North = winds from the north; South = winds from the south.

warm pool. Higher salinities were coincident with this warmer water [Fig. 3(a)]. Anchovy spawning was restricted to the east of this warm water pool [Fig. 3(b)]. Upwelling centers along the Baja California coast brought up 15° – 15.5° C water but did not exclude anchovy spawning [Fig. 3(b)]. Earlier surveys of anchovy larvae distribution show that in most years this geographic area northeast of Guadalupe Island is usually devoid of anchovies (Kramer and Ahlstrom, 1968) but no analysis of oceanographic features has yet been made to confirm whether warm saline water is the reason for this in every case.

Ocean upper mixed layer characteristics

Expendable bathythermographs were deployed along some of the March–April anchovy sampling lines to determine the depth of the mixed layer. Throughout the survey area, the mixed layer was about 50-m deep or deeper. Thus the surface temperatures, as recorded by satellite, accurately reflected definable upper layer water masses and their movements. Upwelling areas similarly were distinct. An examination of Fig. 8 shows that CalCOFI Line 100, off Ensenada, on March 26–27 was characterized by the 60-m deep high-salinity 17° C pool which anchovy avoided during spawning. CalCOFI Line 90, off San Onofre, California, showed contrasting temperature regimes, the coastal warm band (15° – 16° C), and the intrusion of colder (ca. 14° C) water from the north, confirmed by the satellite photo of 6 April shown in Fig. 2. Vertical temperature sections on CalCOFI Line 80, off Pt. Conception, were taken later in April (20 April) but still show the characteristic upslope of the 11° and 12° C isotherms typical of an upwelling regime.

Island Influences

The Channel Islands of Santa Cruz, Santa Rosa, and San Miguel, appear to isolate portions of the Southern California Bight (Pirie and Steller 1977), from the influx of the cold water upwelled from Point Conception (Fig. 5, 28 March 1980).

Circulation in the Southern California Bight seems to be influenced by Santa Catalina Island, as shown in the satellite picture in Fig. 5. Cool water streaming from the north is shielded from the in-shore zone by the island. A warm-water “wake” is apparent in the 28 and 29 March infrared photographs extending 225 km between two colder water masses and persisting for at least 5 days afterwards. Upwelling does not define the shoreward edge of the wake since no upward-sloping isotherms were seen in vertical sections. The R/V *David Starr Jordan* fortuitously crossed this wake on 30 March 1980 while recording sea surface temperature with a thermosalinograph and bucket thermometer. This is shown in Fig. 9, confirming the usefulness of the satellite infrared photograph. This unusual oceanographic feature would have been undetected and its dimensions unrealized from sea surface measurements alone.

Discussion

Because satellites can see vast areas of the ocean day in and day out, they provide the scientist with a synoptic look at processes only seen heretofore on smaller scales and restricted to the times when a ship or ships can cover the area of interest. In this study, only a satellite could have provided us with a synoptic picture of the large scale oceanographic events which were happening over the entire

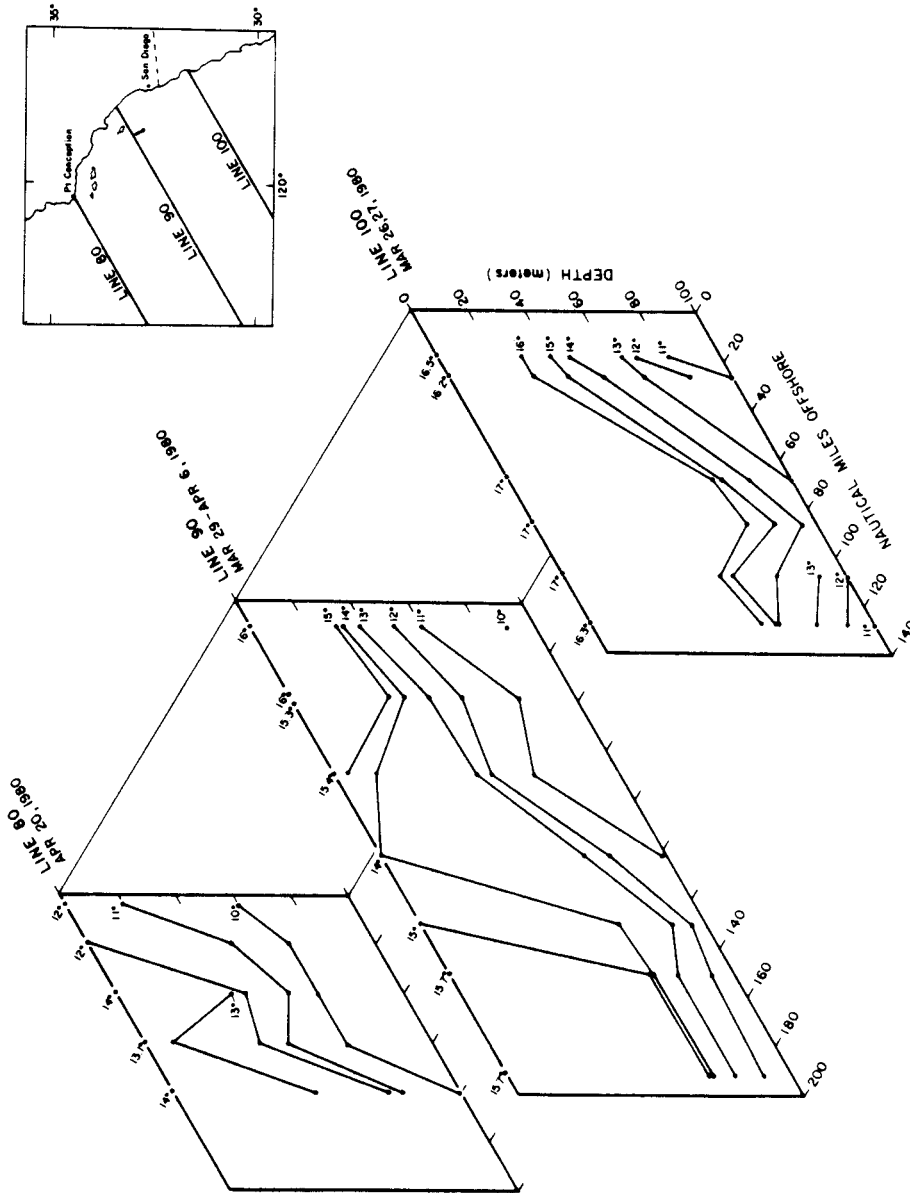


FIGURE 8. Temperature cross sections taken by the R/V *David Starr Jordan* with expendable bathythermographs across the California Current and the Southern California Bight. Line 100, off Ensenada, Baja California, shows that the warm saline pool identified by satellite and surface measurements was about 70-m deep at its deepest point. Line 90, off San Quofre, California showed the southerly extent of a core of cold, upwelled water. Line 80 had 11 and 12°C isotherms sloping up and nearshore, characteristic of an upwelling regime.

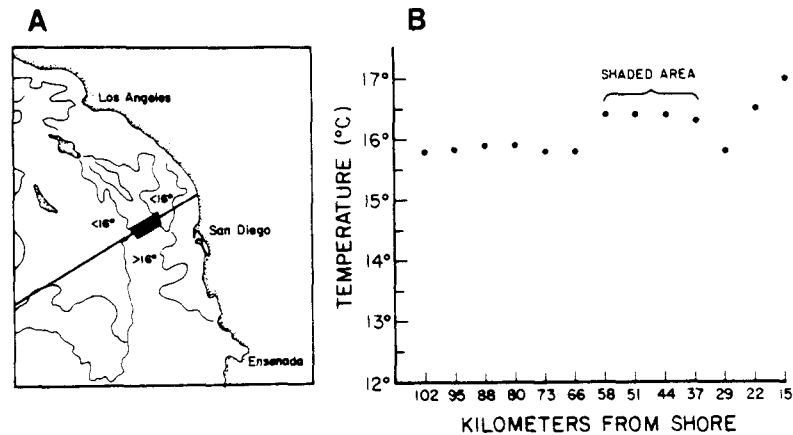


FIGURE 9. Satellite and ship identification of a remarkable wake extending from Santa Catalina Island, 28 March 1980. (a) ship track and temperature contours drawn from satellite photograph shown in Fig. 5. (b) sea surface temperatures recorded by bucket thermometer on the same day.

spawning area of the anchovy during the peak of the spawning season. The extensive ground truth provided by the R/V *David Starr Jordan* confirmed that the 0.5°C accuracy of the infrared radiometer aboard most of the NOAA satellites accurately detects the movement of surface layers and shows the sequential development of upwelling along the California coast over large areas of ocean. The tight correlation between temperature and anchovy spawning was unexpected; when other variables (e.g., salinity) are considered, we are led to the conclusion that temperature is not the environmental variable responsible for anchovy distribution in March–April 1980. Rather, temperature can be used as an indicator of water masses. Sette (1960) in describing ship observations he made in 1940, said, “there was a cold tongue extending down from Pt. Conception into our (sardine) spawning area... the spawning tended to be concentrated around the periphery of this cold tongue.” He went on to state that he believed the spring

bloom of phytoplankton–zooplankton probably occurred at the leading edge of this cold water and that this may have been the reason for sardine spawning there.

Thus, sardines and anchovies respond similarly and some general principles of animal–environment interaction may be responsible for pelagic fish spawning distribution. Satellites permit us to view synoptically vast areas not possible with a ship alone. With sensors for wind, chlorophyll, and wave height, a suite of information may make it possible to use ships more effectively for the study of fish egg and larval distribution and mortality, particularly by judicious deployment of ships guided daily by satellite information. Such information is vital for effective management of certain marine fishery resources.

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R/V David Starr Jordan and other CalCOFI data and to Andrew Bakun who provided the geostrophic wind data. Gary Stauffer was Chief Scientist on the R/V David Starr Jordan during the collections of anchovies and their eggs.

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