SATELLITE REMOTE SENSING OF THE HABITAT OF SPAWNING ANCHOVY IN THE SOUTHERN CALIFORNIA BIGHT

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ABSTRACT

Images of sea-surface temperature and phytoplankton pigments in the Southern California Bight were processed from satellite data obtained during four intensive CalCOFI anchovy egg surveys from 1980 to 1982. Mesoscale patterns of water masses and fronts in the images can explain the distribution of northern anchovy spawning as indicated by first-day eggs. In general, spawning in the northwestern region of the bight is excluded from a cold-water mass south of Point Conception, whereas spawning to the south is confined to coastal waters with moderately high phytoplankton pigment levels. The satellite-measured parameters may indicate critical factors for larval survival. Such satellite images can be used to improve the sampling efficiency of egg surveys.

RESUMEN

Mediante satélites se han obtenido imágenes de la temperatura de la superficie del mar y de pigmentos del fitoplancton, para la zona del seno del sur de California. Estos datos han sido procesados conjuntamente con la información obtenida durante cuatro exploraciones de CalCOFI (1980-1982) para recolectar huevos de anchoa (*Engraulis mordax*).

El contorno de la distribución de masas de agua y frentes en estas imágenes, puede informar sobre la distribución de la actividad de puesta de la anchoa, señalada por la presencia de huevos de un dia en las colecciones. En general, la puesta en la parte noroeste del seno está aislada de la masa de aguas frías al sur de Punta Concepción, mientras que la zona de puesta al sur está confinada a las aguas costeras con niveles relativamente elevados de pigmentos fitoplanctónicos.

Los parámetros medidos por el satélite pueden ser indicadores de factores críticos para la supervivencia de las larvas. Las imágenes proporcionadas por los satélites podrían utilizarse para perfeccionar la eficacia en el muestreo de huevos de anchoa.

INTRODUCTION

Intensive anchovy egg surveys of the CalCOFI region inshore of station 60 have been conducted once or twice yearly since 1980. The Southern California Bight (Figure 1) is the center of distribution of the large central stock of northern anchovy and has been sampled most intensively. The spatial distribution of early stage eggs, indicating recent spawning, corresponds closely to the distribution of adults in night midwater trawls during the spawning season (Figure 2). Temperature and salinity were the only environmental parameters measured routinely on these surveys, although nutrients, phytoplankton pigments, and primary productivity have been measured on some CalCOFI cruises. Vertical egg tows were made at stations 7.4 km apart on transect lines separated by 37 km. This sampling plan gives considerably higher resolution of spatial distribution patterns than does the regular 37- (74-)km CalCOFI station (line) spacing.

Sensors carried on earth-orbiting satellites since 1978 provide high-resolution images of sea-surface temperature and phytoplankton pigment concentration. Accurate estimates of these parameters, corrected for atmospheric scattering and absorption, can be derived from multispectral radiance data. Temperature data are derived from the thermal infrared channels of the Advanced Very High Resolution Radio-

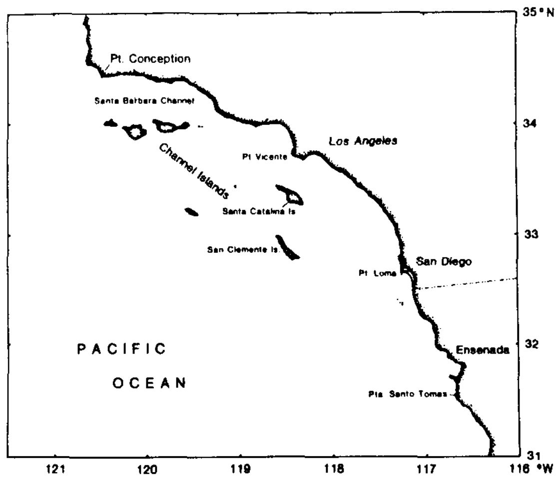

Figure 1. Map of the Southern California Bight.

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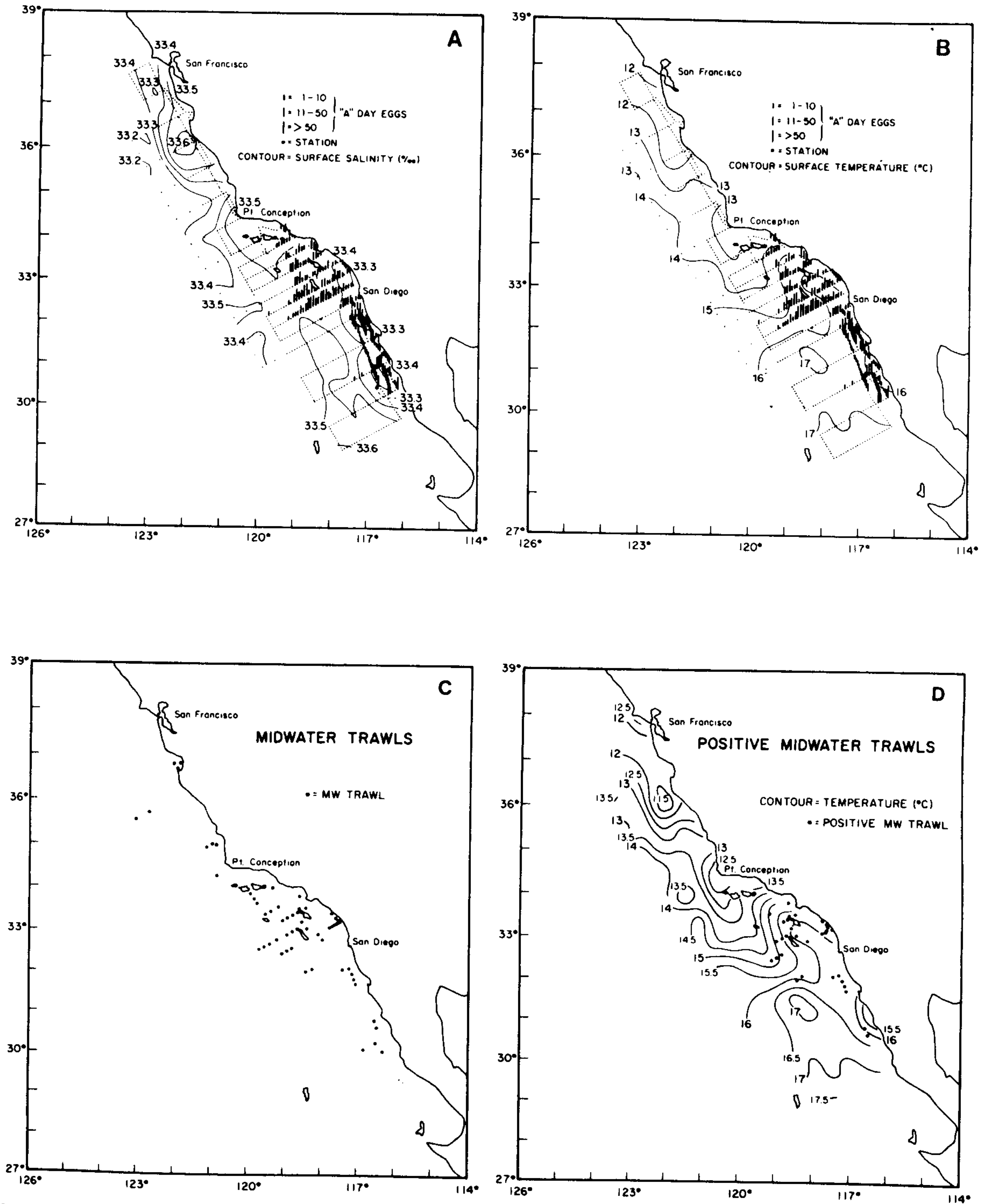

Figure 2. Distribution of anchovy eggs and adults in relation to salinity and temperature, CalCOFI cruise 8003: (*A*) A-day eggs and surface salinity; (*B*) A-day eggs and surface temperature; (*C*) all midwater trawls taken from March 27 to April 12, 1980, by R/V *David Starr Jordan;* (*D*) midwater trawls with adult anchovy catches and surface temperature. From Lasker et al. (1981).

TABLE 1
1980-82 CalCOFI Egg Survey Dates and Stations in the Southern California Bight, and Dates and Times of Corresponding AVHRR and CZCS Images

CalCOFI cruise	Southern California Bight stations		AVHRR *image*	CZCS image
	Dates	N		
8003	20 Mar-10 Apr 1980	359	7 Apr, 1850 PST	8 Apr, 1113 PST
8004	12 Apr-29 Apr 1980	286	—	—
8102	16 Feb- 6 Mar 1981	429	21 Feb, 1955 PST	23 Feb, 1124 PST
8104	31 Mar-12 Apr 1981	373	5 Apr, 2029 PST	4 Apr, 1144 PST
8202	27 Jan-27 Feb 1982	543	29 Jan, 1334 PST	29 Jan, 1109 PST

meter (AVHRR) currently on NOAA-7 and formerly on TIROS-N and NOAA-6. Phytoplankton pigment data are derived from the visible channels of the Coastal Zone Color Scanner (CZCS) on Nimbus-7.

Synoptic images of California coastal waters obtained daily or twice daily and with a resolution of ~1 km give us a much different view of the CalCOFI survey region than is provided by a ship taking hydrographic samples at 37-km intervals on a month-long cruise. This report demonstrates that satellite images define environmental features and boundaries on a scale that helps explain the spatial patterns of spawning activity observed on intensive egg surveys in the Southern California Bight.

DATA AND METHODS

Five intensive egg surveys were completed in 1980-82 (Table 1). Anchovy eggs from vertical egg tows (333-μm-mesh conical net of 25-cm diameter from a depth of 70 m for 1 min) were sorted and staged. Net tows were standardized so that sample counts are equivalent to eggs per 0.05 m^2. Counts of A-day eggs (0-24 hours old) were assumed to represent recent spawning at the station location. Positive egg stations were sorted by egg count into three classes of approximately equal size.

AVHRR infrared data were obtained for the most cloud-free day during each survey, from satellite passes archived at the Scripps Satellite Oceanography Facility (SSOF). Radiance data were converted to temperature using an SSOF radiometric calibration procedure based on Lauritson et al. (1979). Correction for atmospheric water vapor and aerosols, without concomitant sea-truth or atmospheric data, is possible using empirical regressions of ship temperatures on satellite temperatures in two or three thermal infrared bands. The NOAA-6 AVHRR had only two such channels, and the 3.7-μm channel was plagued by excessive noise that steadily increased during the operational lifetime of the satellite. Two-channel correction of the full-resolution NOAA-6 images (8003, 8102, and 8104) was therefore not possible. The 8202 image was corrected with a "split-window" algorithm[1] using channels 4 (10.9μm) and 5 (12.0μm) of the NOAA-7 AVHRR.

Ship-bucket temperatures, obtained at egg tow stations on the same day as the satellite pass, were used to correct the NOAA-6 images. Additive corrections for cold biases of −1.87°, −1.96°, and −1.77°C in the 8003, 8102, and 8104 images yielded root-mean-square differences of 0.50°, 0.52°, and 0.32°C ($n = 27$, 16, and 32 stations). Since corrections based upon linear regression of ship temperatures on satellite temperatures produced only slight improvements (rms differences = 0.36°, 0.32°, and 0.32°C), the simple additive correction was used. Removal of a residual bias of −0.18°C from the corrected 8202 image yielded an rms difference of 0.23°C ($n = 35$).

The Visibility Laboratory of Scripps Institution of Oceanography performed preliminary processing of CZCS data. Band 1 (blue) and band 3 (yellow-green) radiances were corrected for Rayleigh and aerosol scattering by Visibility Lab versions of the CZCS Nimbus Experimental Team's atmospheric algorithm (Smith and Wilson 1981). This algorithm was modified between the dates when the 8003 and 8102 images were processed. The 8104 image was corrected only for Rayleigh scattering, but there was little aerosol contamination visible in the corrected image. Blue/green ratios were converted to phytoplankton pigment concentration (chlorophyll plus phaeopigments) with the pigment algorithm of Smith and Baker (1982). Absolute levels of phytoplankton pigments in the images presented here are not comparable because of the application of different atmospheric correction algorithms and the lack of sea-truth data.

RESULTS

Frequency distributions of ship-bucket temperature measured at stations in the Southern California Bight, and the percentage of positive stations in each temperature interval, are illustrated in Figure 3. Little or no spawning occurred at stations <13.5°C. The warmest

[1]McClain, E. P. 1981. Split-window and triple-window sea surface temperature measurements from satellites. Preprint, Mini-symposium on Applications of Aerospace Remote Sensing in Marine Research, ICES Statutory Meeting, Woods Hole, Mass., 6-10 October 1981.

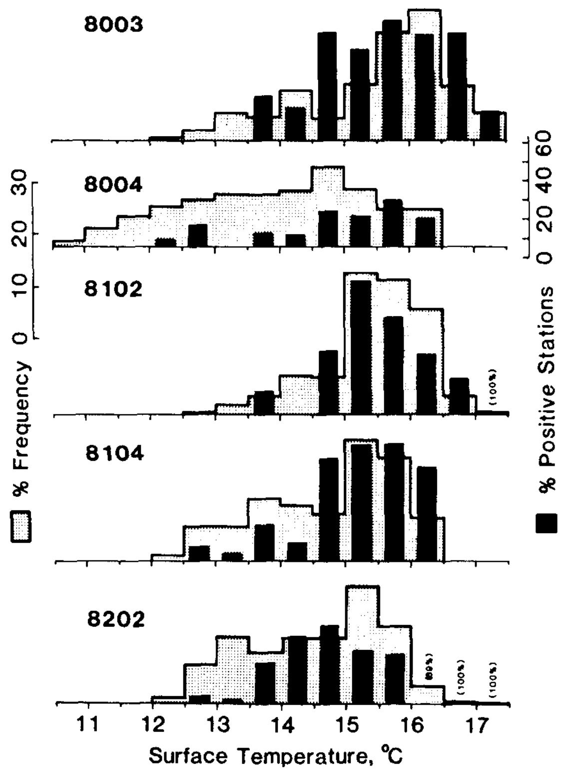

Figure 3. Frequency distributions of CalCOFI stations by surface temperature, and frequency of positive A-day anchovy egg catches within each temperature interval, for five intensive egg surveys. Large percentages of small numbers of stations are in parentheses. Only stations within the Southern California Bight, from line 80 to line 101.6 and no farther offshore than station 60, were included. Extra transects added on cruise 8202 were omitted.

mean surface temperature was observed on cruise 8003 (15.2°C), when spawning occurred most frequently at 14.5-17°C. Mean temperature decreased to 14.4°C during cruise 8004. Spawning was reduced considerably, with eggs found at only 29 of 286 bight stations, and this cruise will not be considered further.

Mean surface temperatures on cruises 8102 (15.1°C) and 8104 (14.7°C) were slightly lower than on 8003, but the modal temperature range of successful spawning did not change. The 1982 egg survey was earlier in the year than 8003 and 8102. Mean surface temperature in the bight was only 14.3°C. The modal spawning temperature range was about 0.5°C colder than in 1980 and 1981, whereas the frequency of successful spawning within that range was generally lower.

The satellite images are enhanced so that low temperatures and high phytoplankton pigment levels appear light, while high temperatures and low pigment levels appear dark. All four pairs of images (Figures 4-7) show the same basic mesoscale features:

1. A plume of cold water upwelled off Point Conception and to the north, and then advected to the south by the California Current. This water has relatively high phytoplankton pigment concentrations.
2. A narrow band of cool water caused by local upwelling along the coast to the east and south of the plume. Occasionally, small plumes extend farther offshore from prominent capes such as Point Vicente, Point Loma, and Punta Santo Tomás. This water has moderately high phytoplankton pigment concentrations.
3. A mass of warm, low-pigment oceanic water extending from the south between the cold-water plume and the coast.

Variations between and within years can be seen in the intensity and size of the mesoscale features and in the detailed shape of frontal boundaries along the coast and around the large cold-water plume. Sea-surface temperature and phytoplankton pigment patterns are somewhat coherent, with an inverse relationship between the two parameters.

8003 (Figure 4a,b)

The cold-water plume defines a boundary on the distribution of spawning activity north of San Clemente Island. The boundary corresponds to approximately the 14.5°C isotherm. Spawning was confined to a 40-km-wide band near the coast south of San Diego. There was no obvious temperature boundary defining this band, although the water offshore was relatively warm (16-17°C). Spawning has been commonly observed in 17-19°C water off Baja California during spring CalCOFI cruises in 1969-79, and Lasker et al. (1981) attributed the offshore absence of spawning in this case to the slightly higher salinity of this warm-water pool (0.1-0.2°/oo; see Figure 1). The phytoplankton pigment image, however, reveals a much more obvious boundary. Spawning is limited to a coastal band of relatively high-pigment water south of San Diego.

8102 (Figure 5a,b)

The cold-water plume at this time extended more to the south than to the southeast, as it did during cruise 8003. Spawning was excluded from the plume north of Santa Catalina Island, although some spawning did occur in relatively cool water in the Santa Barbara Channel (13.5-14°C). Phytoplankton pigment levels from the CZCS were higher than during 8003, a difference that may be due partly to changes in the atmospheric correction algorithm. Although there is

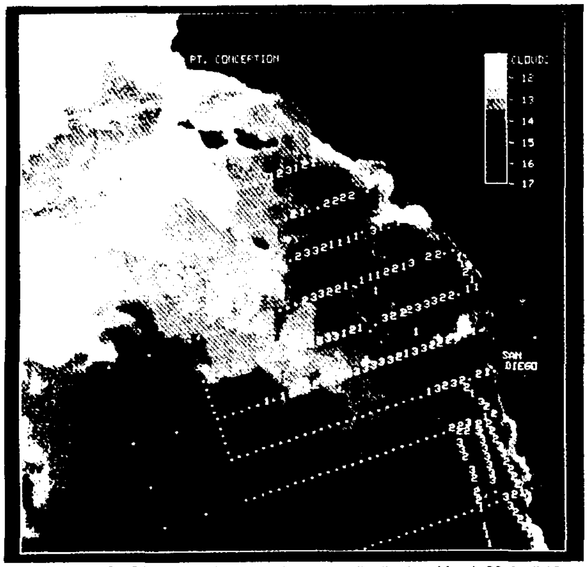

Figure 4a. CalCOFI 8003 A-day anchovy egg distribution, March 20-April 10, 1980. • = 0, 1 = 1-4, 2 = 5-17, 3 = 18-245 eggs/0.05 m^2. Sea-surface temperature (°C) from NOAA-6 AVHRR, channel 4, April 7, 1980.

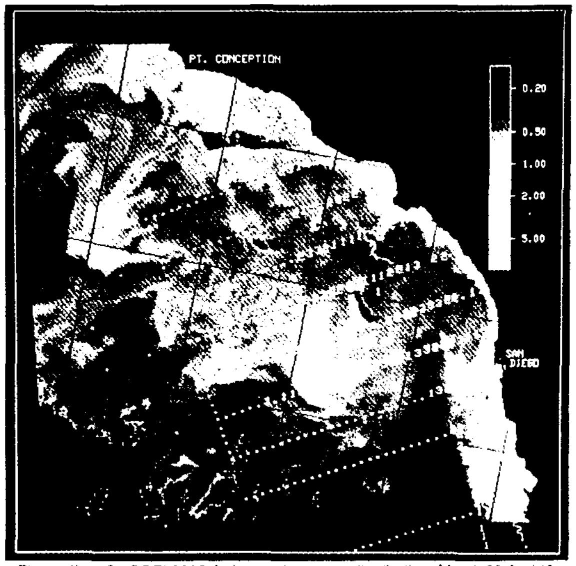

Figure 4b. CalCOFI 8003 A-day anchovy egg distribution, March 20-April 10, 1980. • = 0, 1 = 1-4, 2 = 5-17, 3 = 18-245eggs/0.05m ^{2}. Phytoplankton pigments (mg m^{-3}) from Nimbus-7 CZCS, April 8, 1980.

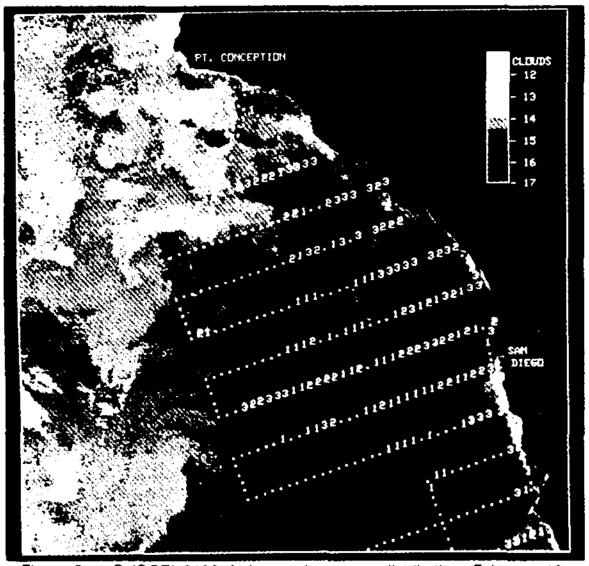

Figure 5a. CalCOFI 8102 A-day anchovy egg distribution, February 12-March 10, 1981. • = 0, 1 = 1-4, 2 = 5-15, 3 = 16-157 eggs/0.05 m^2. *Sea-surface temperature (°C) from NOAA-6 AVHRR, channel 4, February 21, 1981.*

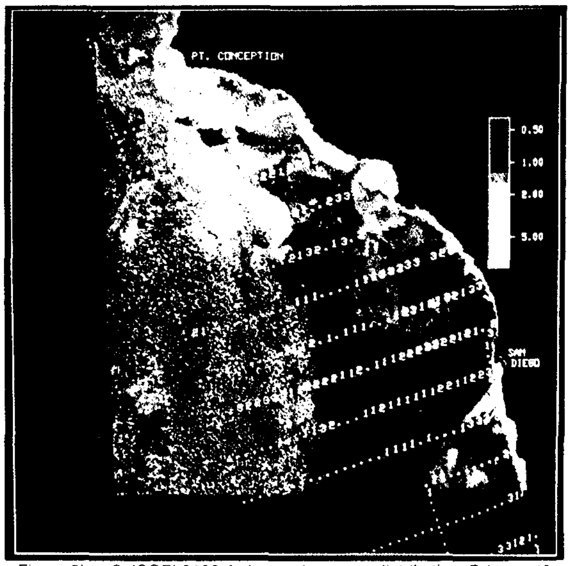

Figure 5b. CalCOFI 8102 A-day anchovy egg distribution, February 12-March 10, 1981. • = 0, 1 = 1-4, 2 = 5-15, 3 = 16-157 eggs/0.05 m^2. Phytoplankton pigments (mg m^{-3}) from Nimbus-7 CZCS, February 23, 1981.

no absolute lower limit on the distribution of spawning apparent in the satellite phytoplankton-pigment image, higher egg abundances south of Santa Catalina Island tended to occur at stations with higher pigment levels ($r = +0.23$, $P = <0.018$, product-moment correlation of log-transformed values).

***8104* (Figure 6a,b)**

Temperatures were generally colder than during 8102, and the cold-water plume extended farther east among the Channel Islands. Spawning did not extend as far to the northwest, although an isolated pocket of spawners remained in the cool Santa Barbara Channel.

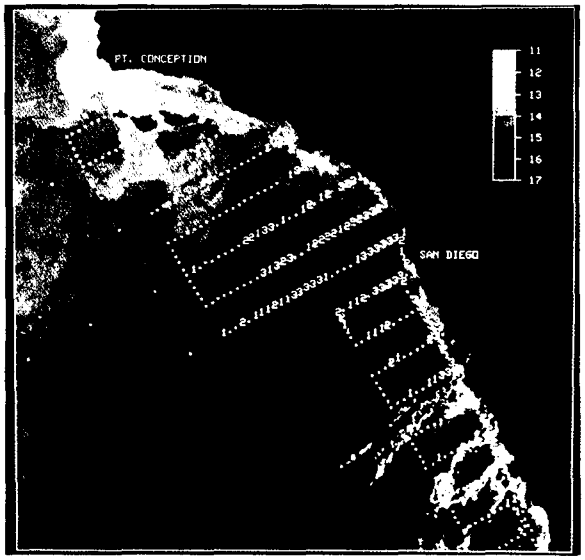

Figure 6a. CalCOFI 8104 A-day anchovy egg distribution, March 31-April 12, 1981. • = 0, 1 = 1-4, 2 = 5-13, 3 = 14-323 eggs/0.05 m². Sea-surface temperature (°C) from NOAA-6 AVHRR, channel 4, April 5, 1981.

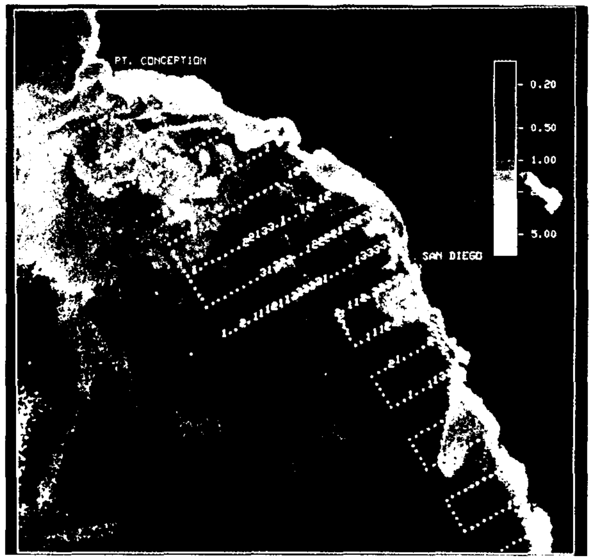

Figure 6b. CalCOFI 8104 A-day anchovy egg distribution, March 31-April 12, 1981. • = 0, 1 = 1-4, 2 = 5-13, 3 = 14-323 eggs/0.05 m². Phytoplankton pigments (mg m⁻³) from Nimbus-7 CZCS, April 4, 1981.

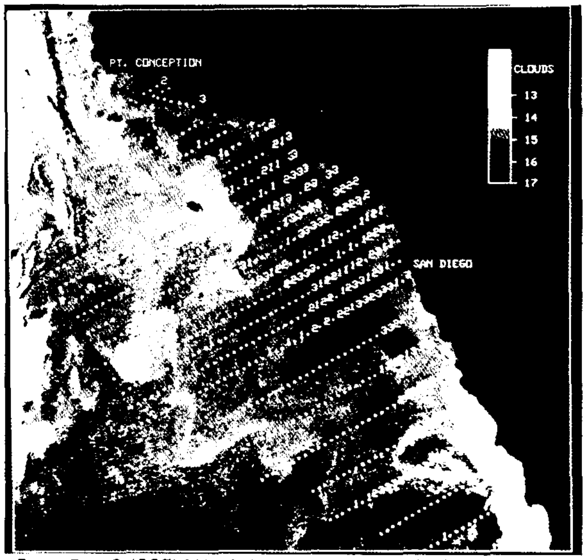

Figure 7a. CalCOFI 8202 A-day anchovy egg distribution, January 27-February 27, 1982. • = 0, 1 = 1-3, 2 = 4-12, 3 = 13-170 eggs/0.05 m². Sea-surface temperature (°C) from NOAA-7 AVHRR, channels 4 and 5, February 18, 1982.

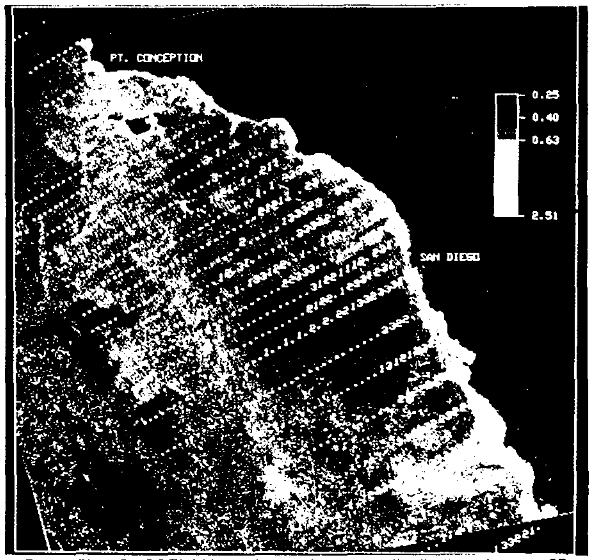

Figure 7b. CalCOFI 8202 A-day anchovy egg distribution, January 27-February 27, 1982. • = 0, 1 = 1-3, 2 = 4-12, 3 = 13-170 eggs/0.05 m². Phytoplankton pigments (mg m^{-3}) from Nimbus-7 CZCS, January 29, 1982.

More spawning occurred south of San Diego, especially in high-pigment waters near the coast.

8202 **(Figure 7a,b)**

Sampling was intensified between lines 83.3 and 95.0 on this survey, with transects separated by 18.5 km. The cold-water plume once again formed a definite boundary on the northwestern extent of spawning activity. To the south, spawning was confined near the coast except off Punta Santo Tomás, south of Ensenada, where a plume of cool water with high phytoplankton pigment levels extended far offshore.

DISCUSSION AND CONCLUSIONS

The satellite images reveal mesoscale and smaller patterns of sea-surface temperature and phytoplankton pigments that define boundaries on northern anchovy spawning in the Southern California Bight. While neither parameter alone is sufficient, both together may define the spatial distributions nearly completely. In general, the northern extent of spawning in the bight, and the offshore extent north of Santa Catalina Island, are limited by cold, upwelled water advected south of Point Conception. Spawning activity to the south is limited by low phytoplankton pigment levels in oceanic water found 20-100km offshore, rather than by temperature.

During cruise 8003, spawning did not occur in water <14°C or <0.2 mg pigments m^{-3} (Figure 8A). At higher temperature and phytoplankton pigment levels, spawning was apparently limited by an interaction, in that the lower temperature limit decreased as pigment concentration increased. A similar relationship holds for cruise 8102 (Figure 8B), although a lower phytoplankton pigment limit was not observed. Note, however, that no eggs were found at many stations with temperature and pigment concentrations within the ranges in which spawning occurred at other stations.

Surface temperature and phytoplankton pigment concentration cannot, therefore, be the only factors determining the distribution of spawning activity. In fact, they may merely indicate more directly important environmental conditions. Spawning in waters favorable for larval survival is an adaptive strategy in the life cycle of many species of fish (Cushing 1975). Lasker (1981) hypothesized that the survival of first-feeding anchovy larvae depends upon the aggregation of nutritionally suitable food organisms in a stratified water column. Large dinoflagellates are preferred food organisms often found in dense near-surface layers in the Southern California Bight.

Satellite observations of relatively warm surface temperatures along with moderately high pigment levels may indicate a stratified water column with a mature phytoplankton community dominated by dinoflagellates. On the other hand, a well-mixed water column would be indicated by colder surface temperatures caused by upwelling or storm mixing; unsuitable food conditions would be indicated either by the low phytoplankton pigment levels of unproductive oceanic water or by very high levels associated with surface diatom blooms in recently upwelled water.

Satellite images of temperature and phytoplankton pigments are "snapshots" of the surface waters of the anchovy environment. Although smaller-scale features change noticeably on time scales of a few days, mesoscale patterns in the Southern California Bight may change little during a 2- to 4-week CalCOFI egg survey (Bernstein et al. 1977). Therefore, satellite data can supplement a survey's environmental data by providing higher-resolution views of sea-surface temperature covering regions larger than the survey grid and by providing estimates of phytoplankton pigment concentrations not normally measured on the surveys. The images presented here demonstrate the utility of satellite data for interpreting spatial distributions from fishery surveys.

Rapid collection and processing of satellite data allow real-time application in planning oceanographic

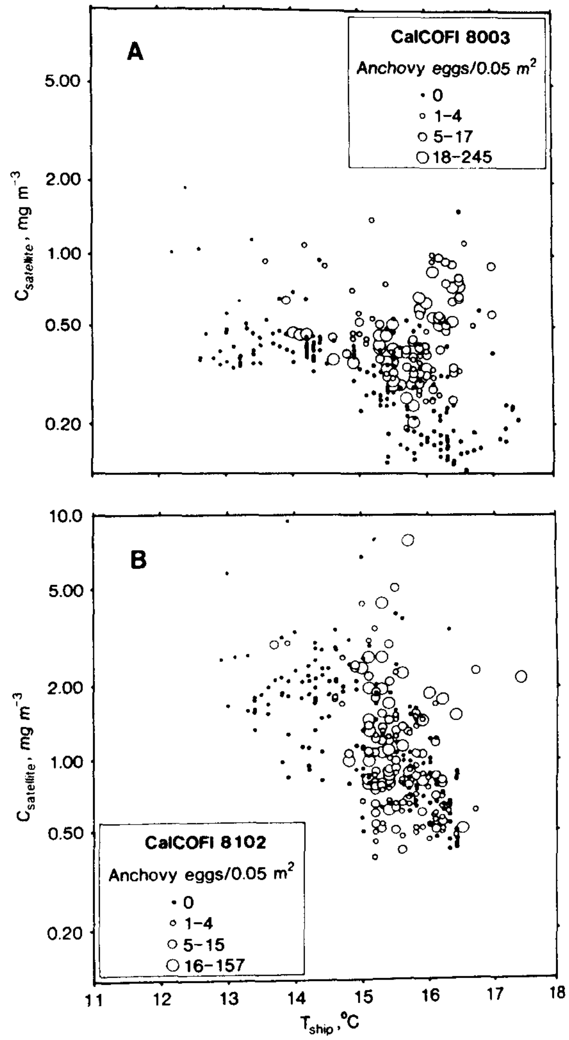

Figure 8. Anchovy A-day egg abundance vs ship-bucket temperature (T ship) and satellite chlorophyll (phytoplankton pigment) concentration. (*A*) Cruise 8003. (*B*) Cruise 8102.

cruises. The primary objective of CalCOFI egg surveys is to estimate anchovy spawning biomass for calculating optimum yield according to the Northern Anchovy Fishery Management Plan. The efficiency of these surveys could improve tremendously if satellite images were used to omit portions of the sampling grid where environmental conditions preclude spawning. This application is currently being explored, but will require a quantitive formulation of the relationships demonstrated here.

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