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THE USE OF SATELLITE INFRARED IMAGERY FOR DESCRIBING OCEAN PROCESSES IN RELATION TO SPAWNING OF THE NORTHERN ANCHOVY (*ENGRAULIS MORDAX*)

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ABSTRACT

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 $\leqslant 14°$ C water 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 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 was 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 U.S./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, March 14 to April 14, 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 infra-red 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 March 14, 1980 through April 14, 1980. The area studied extended from approximately Monterey Bay, California (37°N, 122°W) to Vizcaino Bay, Baja California (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 took place at temperatures above 16.5° C and in water colder than 14° C. The 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 temperature 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 observations, a storm swept through the area on April 1 and 2 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

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 April 6 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 Southern California Bight (Figure 3B 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 March 28 shown in Figure 5 of the California Current and the coast of California and Baja California illustrates the features just described. In the right hand portion of the figure 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 Figure 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 is also shown in Figure 6 (upper). In earlier years appreciable spawning plume, once formed, advanced southward, carried by the California Current, retaining its basic shape, in ladder-like sequence (see also Figure 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, March 27 to April 12 (Figure 2). Sea surface temperature isotherms derived from satellite imagery compare remarkably well with those from shipboard observations as shown at the bottom of Figure 2. Salinities taken concurrently (see Figure 3A and 3B) 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, Roden and Wyllie, 1958).

Anchovy Spawning in the Southern California Bight and Cold-Water Intrusion from Northern California Upwelling Centers

Despite the "snapshot" nature of April 6 infrared imagery (Figure 2) of the Southern California Bight, previous and subsequent photographs show clearly that the meso-scale 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 meso-scale thermal features off California was first described by Bernstein, Breaker and Whritner (1977). Thus the biological sampling done over a few days can be compared to a single day's infrared image.

survey (CalCOFI) lines (Kramer et al. 1972) and at more closely spaced intervals in selected areas.

A vertical plankton tow of 1 minute duration was taken from 70 m deep with a .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 (961) stations were sampled in water ranging from 11° to 17.5° C. Fifty-two (52) 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 (March 19 and March 28) for the Southern California Bight reproduced in Figure 1, top and bottom respectively, illustrate the evolution of coastal upwelling plumes orginating 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 each 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 minimal, judging from average wind speed at Pt. Conception (Figure 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 (Figure 3C and D). The start of upwelling on March 14 and the progressively colder temperatures appeared to have excluded anchovies from that time on. The leading edge of the cold-water mass generated March 14 by upwelling off Pt. Conception by April 6 travelled south approximately 300 km at a rate of about 12.5 km per day.

Exclusion of Anchovies from a Warm Saline Zone off Baja California

Satellite pictures (Figure 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 (Figure 6) but spawning in 1980, however, was restricted to a band 40 km wide, parallel to the Baja California coast avoiding this warm pool. Higher salinities were coincident with this warmer water (Figure 3A). Anchovy spawning was restricted to the east of this warm water pool (Figure 3B). Upwelling centers along the Baja California coast brought up 15°-15.5° C water but did not exclude anchovy spawning (Figure 3B). 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 Figure 9 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 April 6 shown in Figure 2. Vertical temperature sections on CalCOFI Line 80, off Pt. Conception, were taken later in April (April 20) 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 (Figure 5, March 28, 1980).

Circulation in the Southern California Bight seems to be influenced by Santa Catalina Island, as shown in the satellite picture in Figure 5. Cool water streaming from the north is shielded from the inshore zone by the island. A warm water "wake" is apparent in the March 28 and 29 infrared photographs extending 225 km between two colder water masses and persisted 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 March 30, 1980 while recording sea surface temperature with a thermosalinograph and bucket thermometer. This is shown in Figure 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 area^ 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 time 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 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 detects accurately 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.

ACKNOWLEDGMENTS

We are grateful to Margaret Wolfe who assisted us in our early work at the Scripps Remote Sensing Facility. Thanks also to Richard Charter for development of computer routines which simplified our use of R/V Jordan and other CalCOFI data and to Andrew Bakun who provided the geostrophic wind data. Gary Stauffer was Chief Scientist on the R/V Jordan during the collections of anchovies and their eggs.

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FOOTNOTES

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

FIGURES

Figure 1. NOAA-6 infrared photographs from Pt. Sur, California to Ensenada, Baja California. TOP: Upwelling began along the northern California coast about March 14, 1980 and was well established on March 19 when this photo was taken. BOTTOM: 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.

Figure 2. Match of satellite and ship sea surface temperatures. TOP: April 6, 1980 NOAA-6 infrared photograph showing cold water extending south. BOTTOM: Match of March 27 to April 12 ship surface temperature observations with contoured gray scale-derived temperatures (April 6, 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 March 27 to April 12, 1980 by R/V David Starr Jordan. D: Adult anchovy catches by midwater trawls and temperature distribution. Compare this with Figure 4B.

Figure 4. Distribution of anchovy eggs superimposed on the thermal image of the Southern California Bight taken April 6, 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.

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

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

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

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 Onofre, California showed the southerly extent of a core of cold, upwelled water. Line 80 had 11 & 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, March 28, 1980. A: ship track and temperature contours drawn from satellite photograph shown in Figure 5. B: sea surface temperatures recorded by bucket thermometer on the same day.

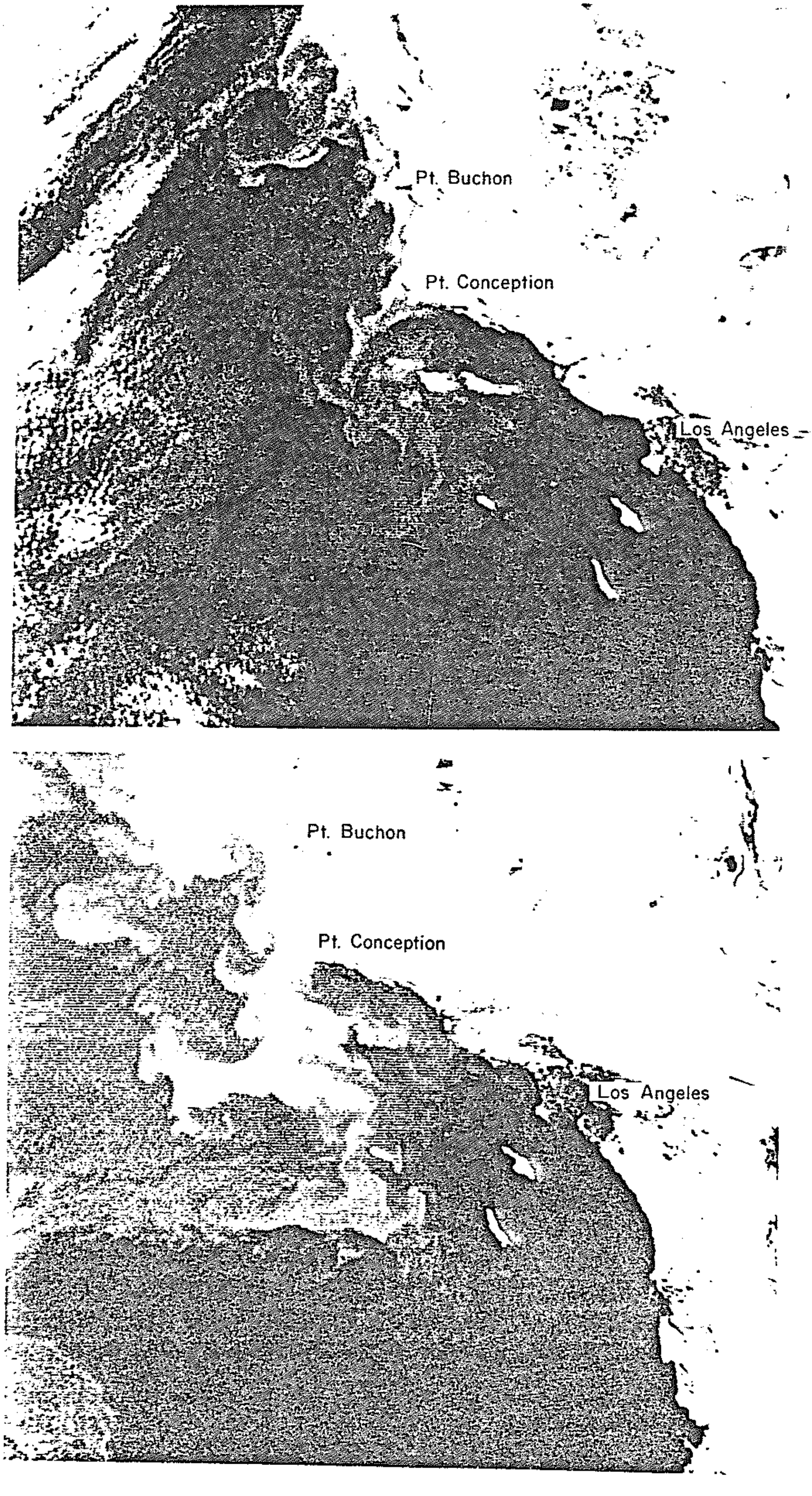
Pt. Buchon
Pt. Conception
Los Angeles
Pt. Buchon
Pt. Conception
Los Angeles

Fig 1

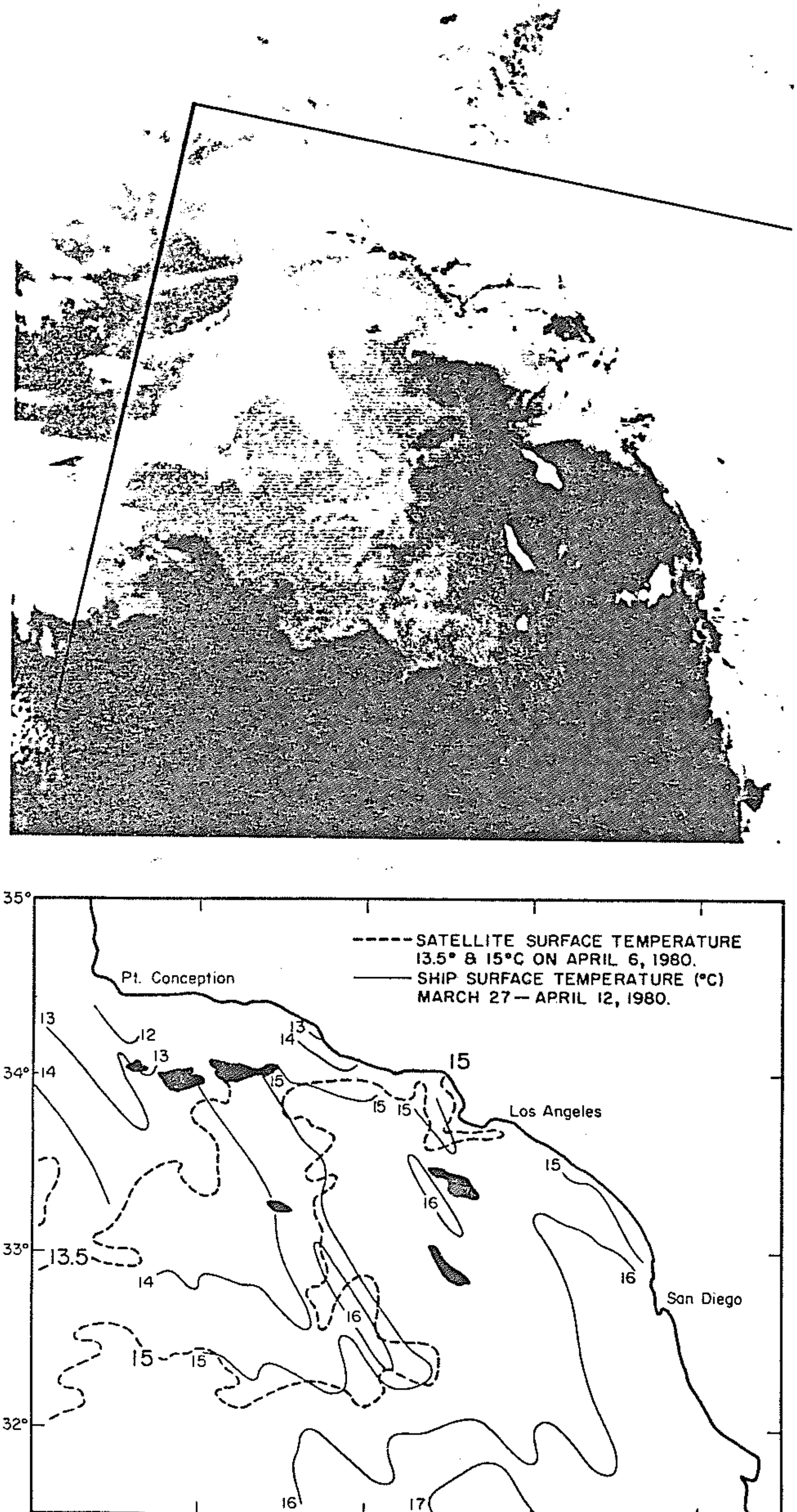
----- SATELLITE SURFACE TEMPERATURE
13.5° & 15°C ON APRIL 6, 1980.
—— SHIP SURFACE TEMPERATURE (°C)
MARCH 27—APRIL 12, 1980.
Pt. Conception
Los Angeles
San Diego
35°
34°
33°
32°
121°
120°
119°
118°
117°
13
14
12
13
13
14
15
15
15
15
15
16
16
13.5
14
16
15
15
16
17

Fig 2

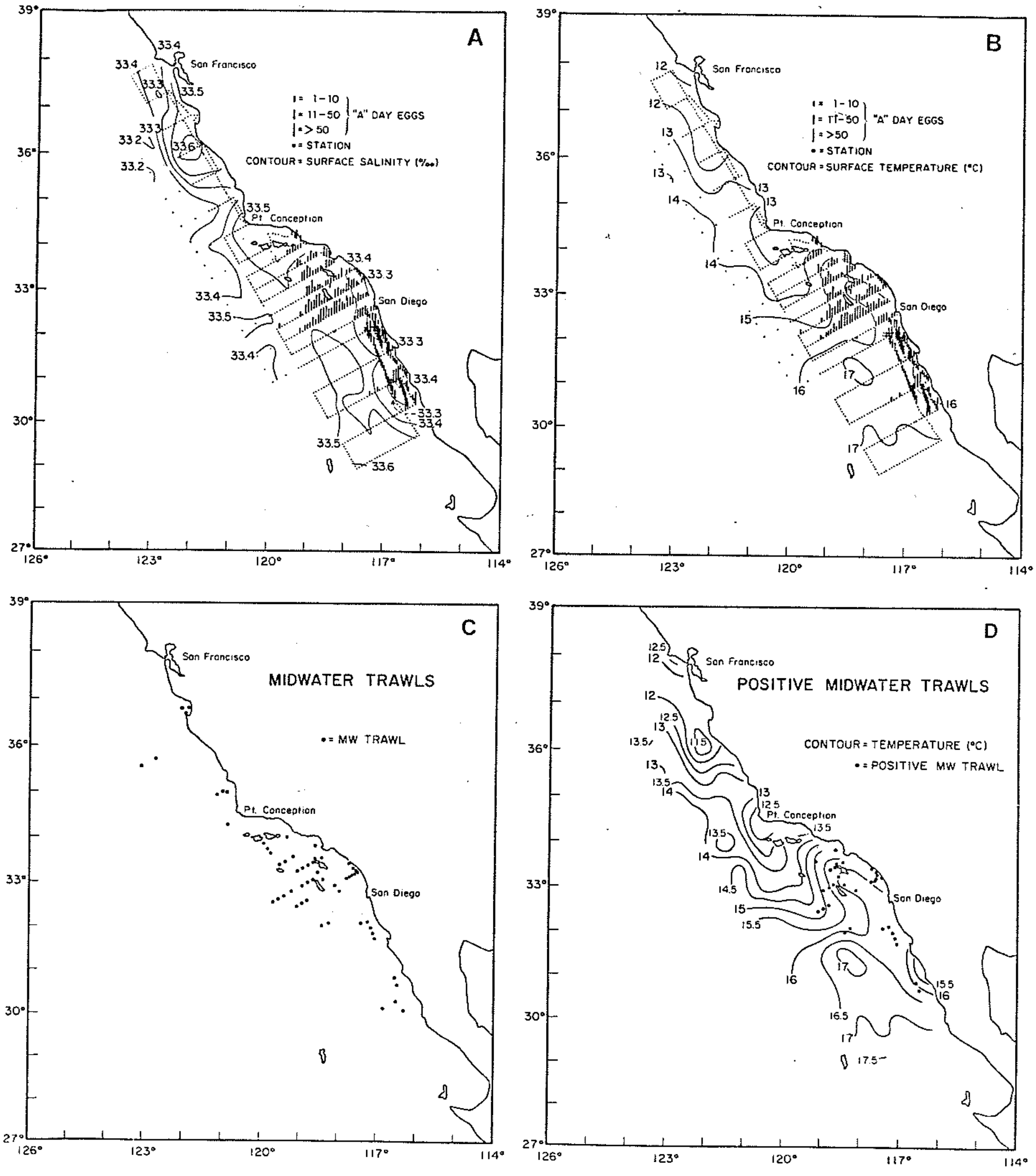
A
San Francisco
Pt. Conception
San Diego
= 1-10
= 11-50
= >50
"A" DAY EGGS
• = STATION
CONTOUR = SURFACE SALINITY (‰)
33.4
33.3
33.5
33.6
33.2
B
San Francisco
Pt. Conception
San Diego
= 1-10
= 11-50
= >50
"A" DAY EGGS
• = STATION
CONTOUR = SURFACE TEMPERATURE (°C)
12
13
14
15
16
17
C
San Francisco
Pt. Conception
San Diego
MIDWATER TRAWLS
• = MW TRAWL
D
San Francisco
Pt. Conception
San Diego
POSITIVE MIDWATER TRAWLS
CONTOUR = TEMPERATURE (°C)
• = POSITIVE MW TRAWL
12.5
12
13
13.5
14
14.5
15
15.5
16
16.5
17
17.5
39°
36°
33°
30°
27°
126°
123°
120°
117°
114°

Fig 3

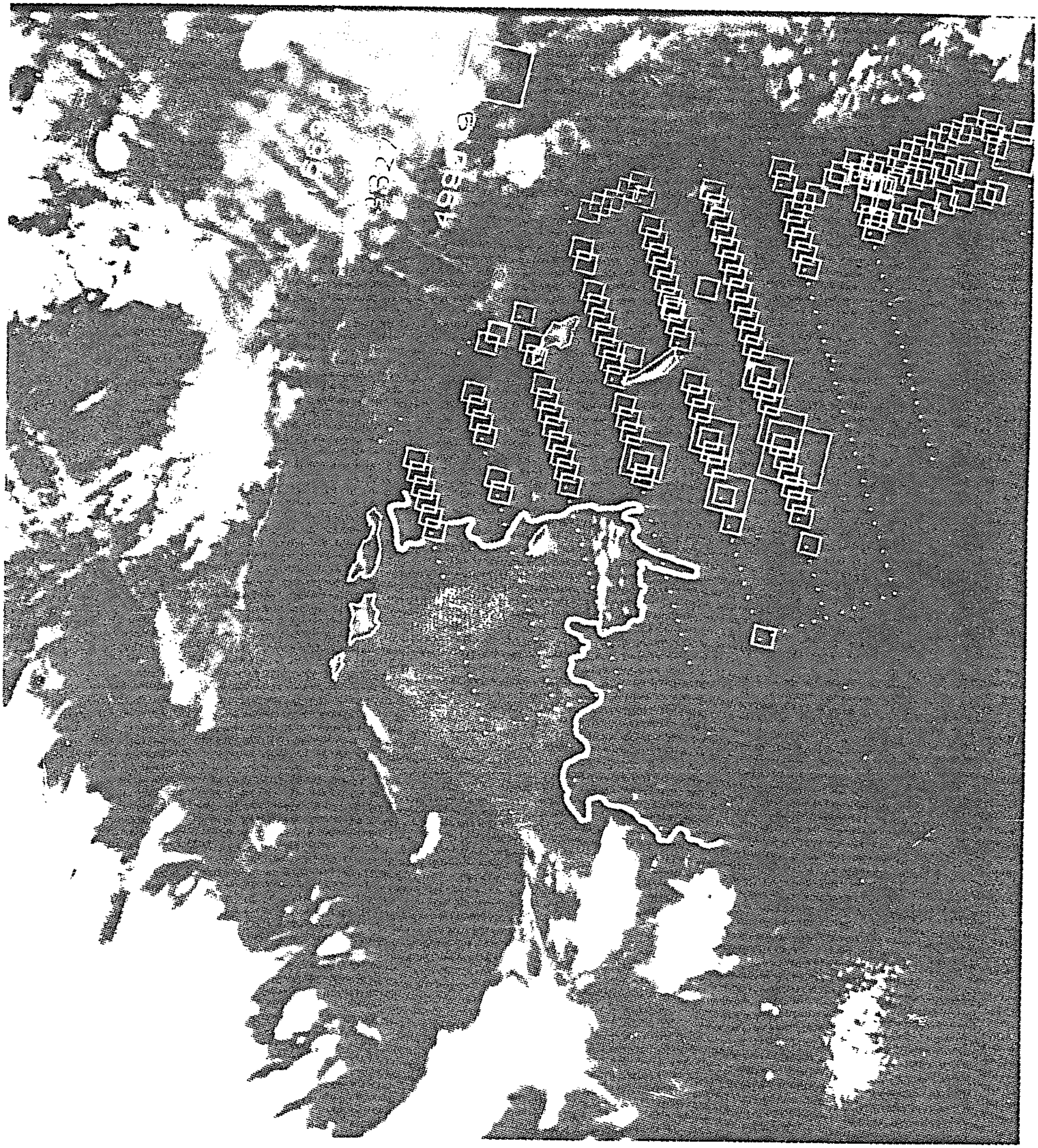

Fig. 4

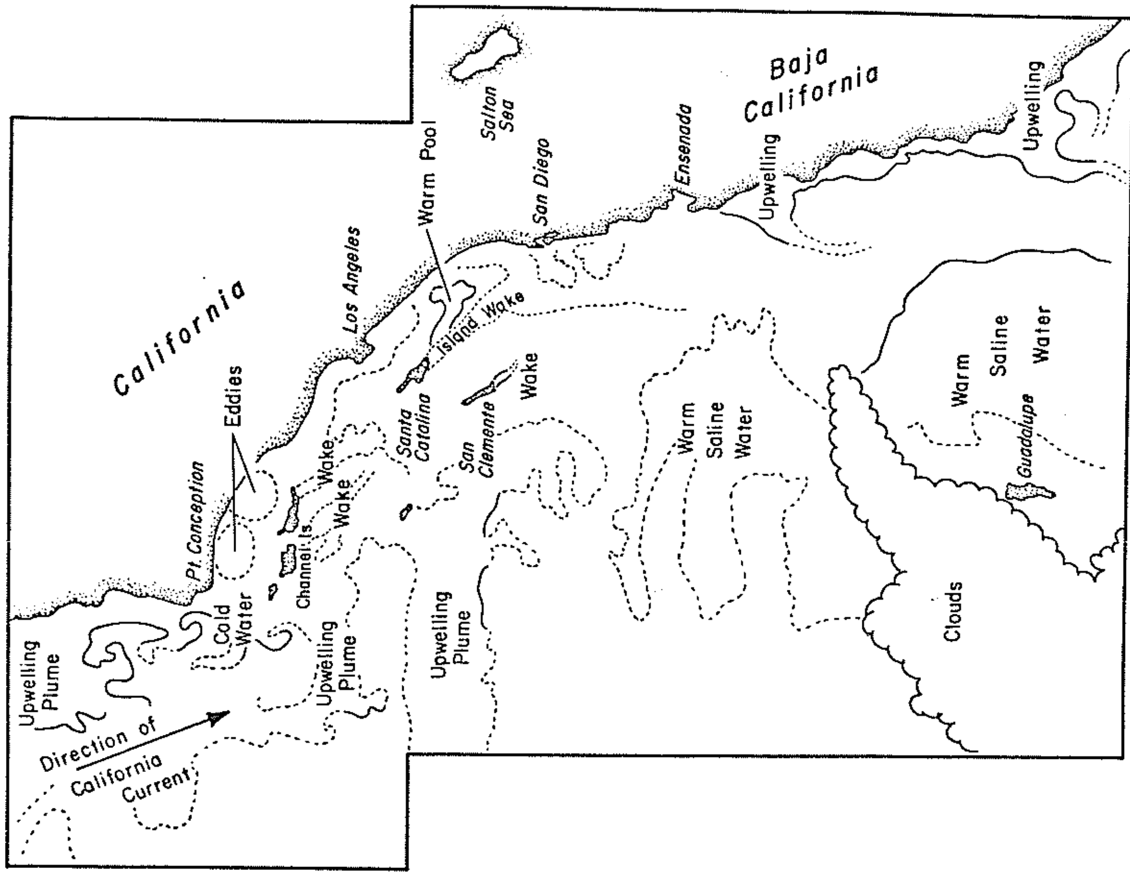
California
Baja California
Salton Sea
Warm Pool
San Diego
Ensenada
Upwelling
Los Angeles
Island Wake
Eddies
Pt. Conception
Santa Catalina
San Clemente
Wake
Channel Is.
Cold Water
Upwelling Plume
Direction of California Current
Warm Saline Water
Guadalupe
Clouds

Fig 5

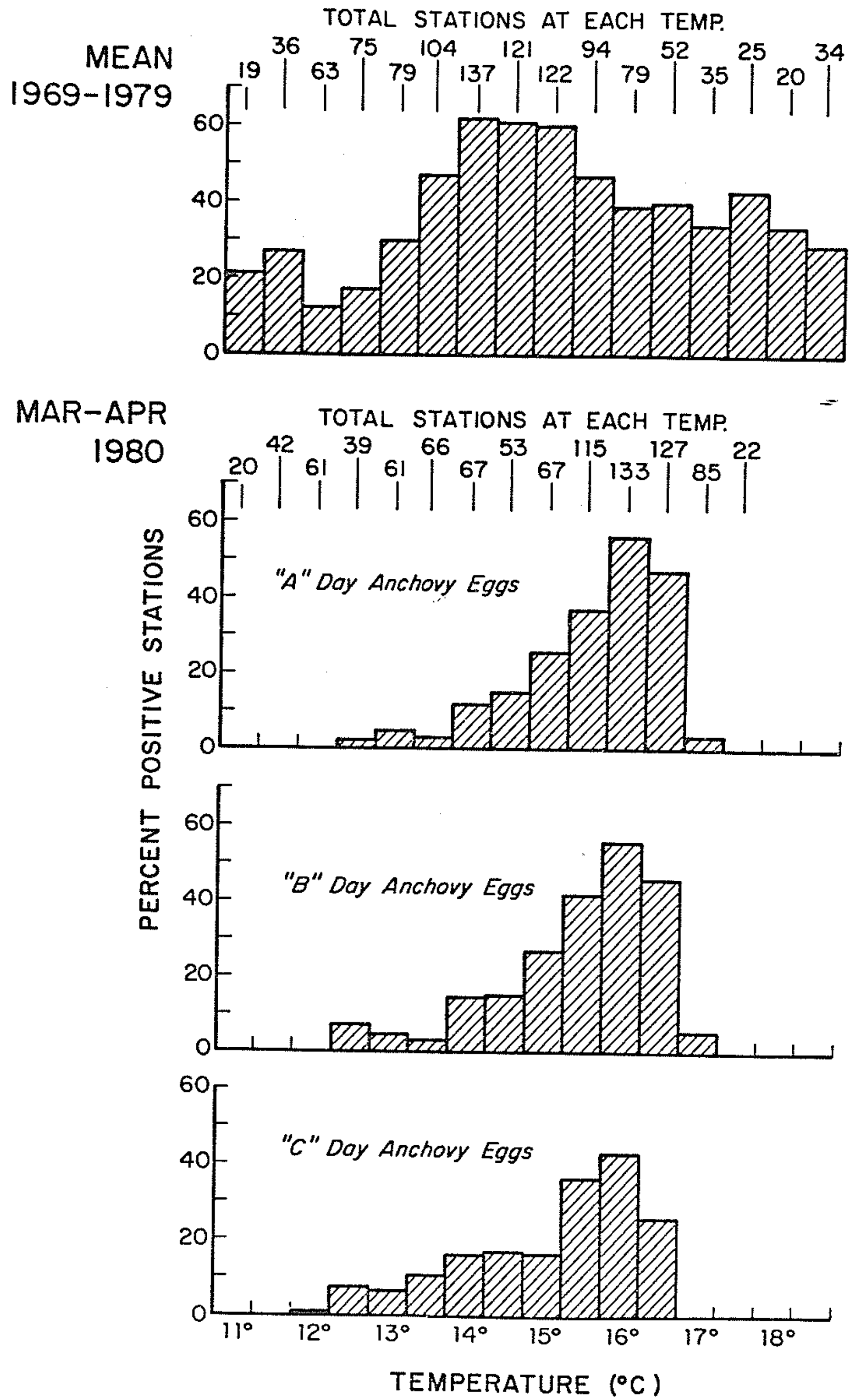
TOTAL STATIONS AT EACH TEMP.
MEAN
1969-1979
19 36 63 75 79 104 137 121 122 94 79 52 35 25 20 34
0
20
40
60
MAR-APR
1980
TOTAL STATIONS AT EACH TEMP.
20 42 61 39 61 66 67 53 67 115 133 127 85 22
PERCENT POSITIVE STATIONS
"A" Day Anchovy Eggs
"B" Day Anchovy Eggs
"C" Day Anchovy Eggs
11° 12° 13° 14° 15° 16° 17° 18°
TEMPERATURE (°C)

Fig 6

AVERAGE WIND SPEED PER DAY (m/sec)

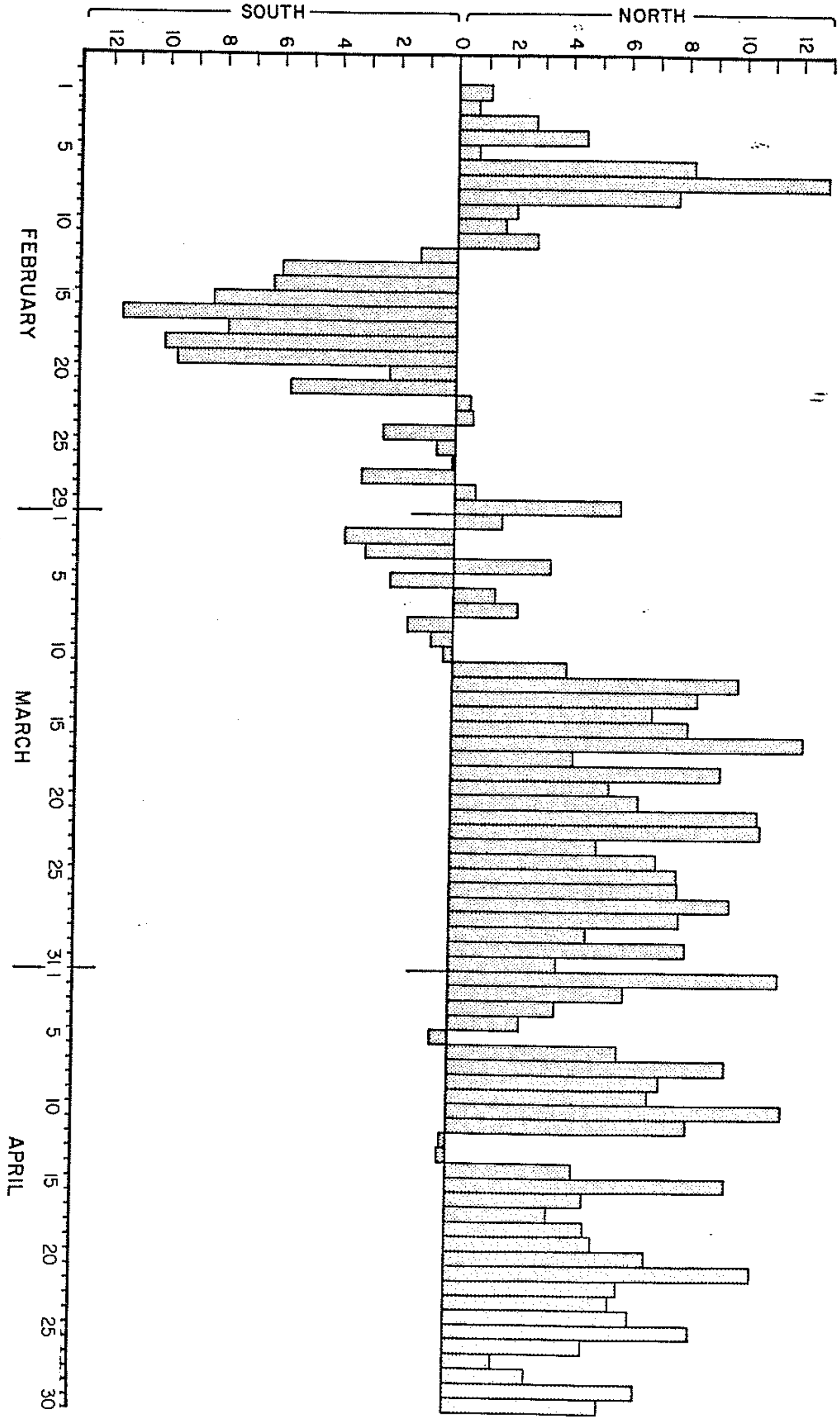

Fig 7

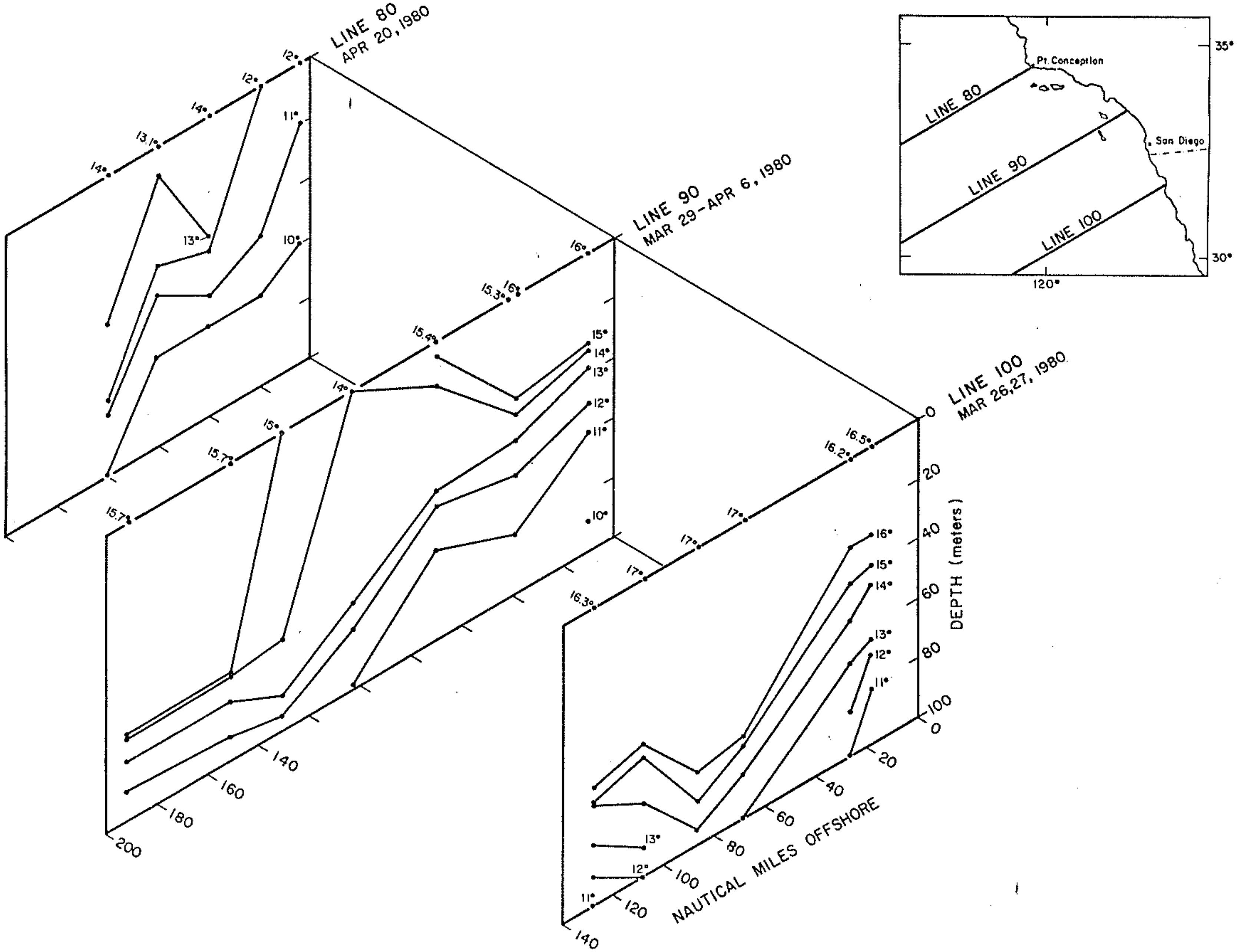
LINE 80
APR 20, 1980
LINE 90
MAR 29-APR 6, 1980
LINE 100
MAR 26,27, 1980
DEPTH (meters)
NAUTICAL MILES OFFSHORE
Pt. Conception
San Diego
35°
30°
120°

Fig 8

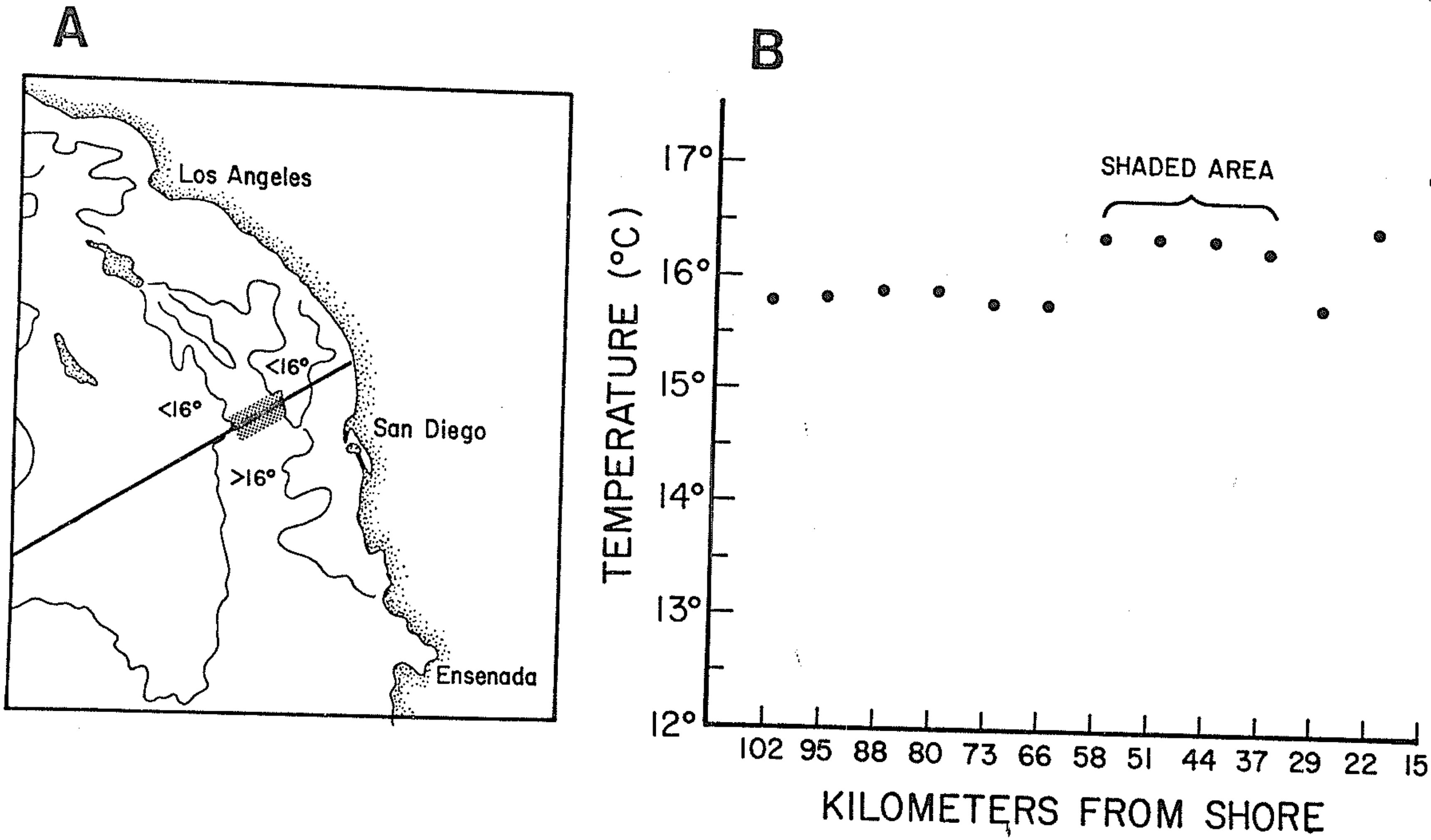
A
Los Angeles
San Diego
Ensenada
<16°
<16°
>16°
B
SHADED AREA
TEMPERATURE (°C)
17°
16°
15°
14°
13°
12°
102 95 88 80 73 66 58 51 44 37 29 22 15
KILOMETERS FROM SHORE

Fig 9