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Albacore tuna catch distributions relative to environmental features observed from satellites

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Abstract—Albacore tuna catch data from the summer of 1981 are displayed on concurrent satellite images of sea surface temperature and phytoplankton pigment concentration, from the NOAA-7 Advanced Very High Resolution Radiometer (AVHRR) and the Nimbus-7 Coastal Zone Color Scanner (CZCS), respectively. During 3 week-long periods off California, intense fishing activity and larger catches, indicating aggregations of albacore, were located within pockets of warm, blue oceanic water intruding into the boundary between oceanic and cooler greenish coastal waters. A relatively productive oceanic region, defined by a color front visible in a CZCS image, was the site of albacore aggregation in waters several hundred miles offshore during the first 2 weeks of September 1981.

INTRODUCTION

Albacore, *Thunnus alalunga*, is a highly migratory tuna that supports important United States commercial and recreational fisheries and several foreign fisheries in the North Pacific. Albacore are found off the coast of North America from central Baja California to British Columbia, Canada, from late spring to autumn.

The migration, distribution, availability, and catchability of albacore are markedly influenced by oceanographic conditions in the North Pacific, notably hydrographic fronts. For example, albacore fishing grounds in the western Pacific have been linked to oceanic fronts in the region of the Kuroshio current and Kuroshio Extension waters (Uda, 1973). Seasonal migration into North American coastal waters is associated with the Transition Zone and its frontal boundaries (Laurs and Lynn, 1977). Coastal upwelling fronts and fronts at the margin of river plumes influence local concentrations and movements of albacore in United States coastal waters (Pearcy and Mueller, 1970; Laurs *et al.*, 1977). Albacore fishermen traditionally fish blue, oceanic waters warmer than 15°C and near fronts indicated by temperature or water color 'breaks'. Fishing grounds are often found associated with undersea topographic features, such as seamounts and banks, which are believed to be sites of local enrichment and food abundance (Dotson, 1980; Sund *et al.*, 1981).

Optimum temperature ranges for albacore catch have been determined from commercial or research vessel catches and sea surface temperature measurements (Alverson, 1961; Clemens, 1961). However, documentation of an association between albacore and thermal

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or color fronts has not been possible due to the difficulty of obtaining concurrent catch and hydrographic data covering sufficiently large areas. LAURS *et al.* (1977) used a different approach by sampling a small area around single albacore located by ultrasonic tracking and observed movements constrained by local temperature boundaries. Early attempts to detect environmental limits on tuna distributions from aircraft and satellites had some limited success (PEARCY and MUELLER, 1970; STEVENSON and MILLER, 1974).

Earth-orbiting satellites flown since 1978 rapidly provide data yielding images of sea surface temperature and the turbidity and phytoplankton pigment concentration of near-surface waters over large areas of the ocean. Some of the data are used to provide west coast fishermen with sea surface temperature and ocean color boundary charts (BREAKER, 1981; MONTGOMERY, 1981), although the benefits of such services have not yet been rigorously evaluated. This paper will show that environmental features observed in satellite i.r. and color images of the sea surface define boundaries for albacore aggregations and optimum fishing regions indicated by daily catch data.

METHODS

Concurrent satellite and fish catch data were obtained through a unique information network involving the cooperation of the Scripps Institution of Oceanography Satellite Oceanography Facility (SSOF), the Scripps Visibility Laboratory, the National Marine Fisheries Service, the California Department of Fish and Game, and the Oregon Department of Fish and Wildlife (Fig. 1). Coastal Zone Color Scanner (CZCS) data were received at the SSOF directly from the Nimbus-7 satellite and processed at the Visibility Laboratory. Data from three passes over coastal waters off California and one pass covering a region offshore of Oregon and Washington were obtained during periods of heavy fishing activity in August and September 1981 (Fig. 2). Two of the passes over coastal waters had been used to produce experimental ocean color boundary charts for distribution to a limited number of fishermen (MONTGOMERY, 1981).

Band 1 (blue) and Band 3 (green) radiances were corrected for Rayleigh and aerosol scattering by a Visibility Laboratory-modified version of the CZCS Nimbus Experimental Team's atmospheric algorithm (SMITH and WILSON, 1981). We converted the blue:green color ratio to phytoplankton pigment concentration using the pigment algorithm by CLARK (1981). Pigment values are not comparable between images due to ongoing modifications of the atmospheric algorithm during the months when the images were processed. The principal source of uncertainty was the progressive decay in the CZCS's radiometric sensitivity. The decay was known but poorly quantified when the images were processed. The coastal images are one-half normal resolution with only one of every 2 × 2-block of pixels retained, so that each pixel represents an area with dimensions of 1.6 km. The offshore image is one-third normal resolution (2.4 km).

NOAA-7 Advanced Very High Resolution Radiometer (AVHRR) i.r. data corresponding to the CZCS images were obtained from satellite passes archived at the SSOF. Channel 4 (10.5 to 11.3 μm) and Channel 5 (11.5 to 12.5 μm) radiances were converted to temperature using an SSOF radiometric calibration procedure based on LAURITSON *et al.* (1979). Sea surface temperatures corrected for atmospheric effects were estimated using the split-window algorithm proposed by MCCLAIN *et al.* (1983). Finally, the sea surface temperature images were registered to ground control points taken from the ocean color images, so that the earth locations of the two images are identical.

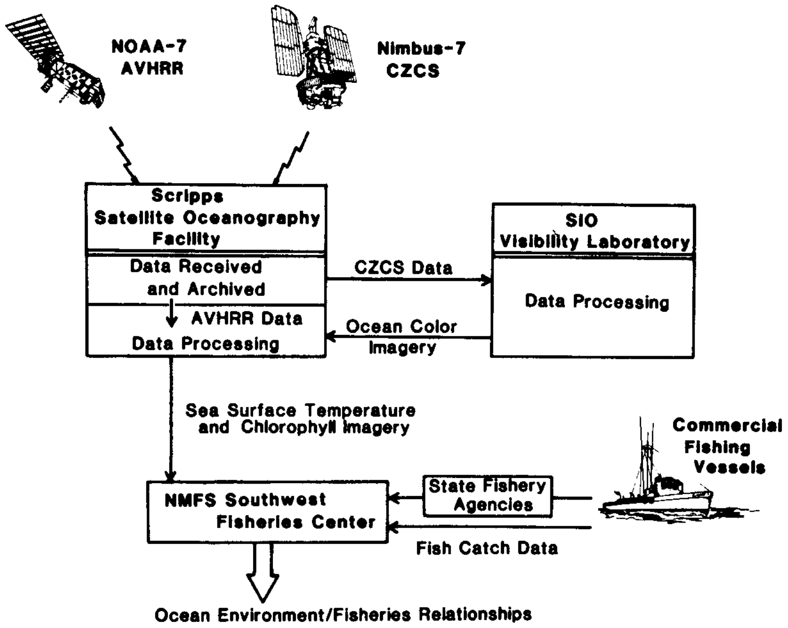

Fig. 1. Satellite data collection and processing network utilized by the National Marine Fisheries Service, Southwest Fisheries Center.

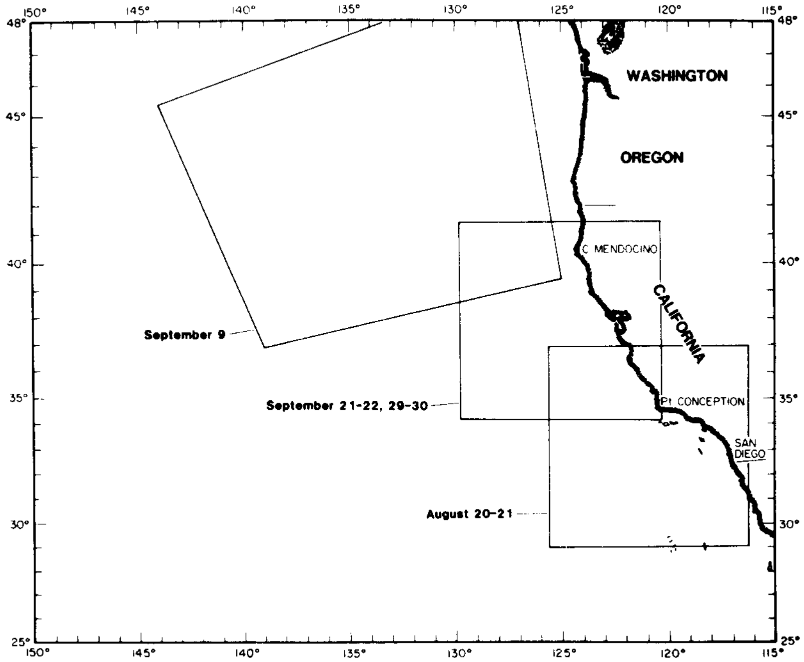

Fig. 2. Locations of satellite images.

Albacore catch data were obtained from daily logs submitted by fishermen (LAURS *et al.*, 1975). Positions were usually recorded at the start of a day's fishing activity, which may cover up to 50 km. Catches were normalized to 150 line-hours, a typical full day of effort by an albacore trolling or jig boat. Catch data for periods from 2 days before to 2 days after each pair of satellite passes were plotted on the satellite temperature and phytoplankton pigment images. The offshore catch data (1 to 15 September 1981) are means from 1° squares. Fishing boats do not randomly sample the albacore population; there is communication among boats and a fleet will aggregate in productive fishing regions, based on current fishing success and traditional indicators such as water temperature, color, sea bird activity, etc.

The AVHRR images presented here are enhanced so that sea surface temperature ranges from warm (nearly black) to cold (nearly white). The CZCS images are false-color enhanced. Land is masked with black, while clouds appear white in the SST images and black in the chlorophyll images. The grey and color scales are not consistent between images, in order to optimally define ocean features.

RESULTS

In Fig. 3 (20 to 21 August) a coastal water mass characterized by low temperature ($<15°C$) and high phytoplankton pigments (>0.60 mg m^{-3}) was evident north of Pt. Conception. The large plume of this water extending offshore to the south was a feature present for most of the year in the region. Fishing activity during 18 to 23 August was concentrated east of the plume in warm ($>16°C$) and blue (<0.30 mg pigments m^{-3}) oceanic water, as measured from the satellites. Only small catches were reported within the coastal water plume. The largest catches were in two pockets of oceanic water on the eastern edge of the plume. In the northern pocket (not covered by the CZCS image), large catches were located close to the thermal front at the oceanic-coastal boundary. Fishing activity in the northern pocket peaked on 20 August, while activity in the southern pocket peaked on 17 August. Eastward movement of the southern pocket between 17 August and the satellite passes may explain the greater apparent separation between fishing activity and the front.

In Fig. 4 (21 to 22 September) and Fig. 5 (29 to 30 September), an intense and meandering frontal boundary extended south from Cape Mendocino, possibly associated with upwelling there and off Pt. Arena to the south. The SST and color fronts correspond almost exactly, although the 29 September color front was more diffuse than the 30 September SST front. Differences between concurrent images are due primarily to displacement of small-scale features and to the linear enhancement algorithms. The basic pattern of the front changed slightly over the 1-week period between the two sets of images. Note the changes in the shapes of the two pockets of warm, low-pigment water just south of Cape Mendocino. During 19 to 24 September and 27 September to 2 October, fishing boats were aggregated and took the largest catches in these two pockets of oceanic water. Some small catches were reported on the coastal side of the front and within the narrow cold-water plume northwest of Cape Mendocino.

Figure 6 (9 September) covers a large oceanic region off the coasts of Washington and Oregon (Fig. 2). Sea surface temperature increased gradually from 12°C at 48°N to 20°C at 40°N, and no temperature fronts were visible in the AVHRR image. However, a diffuse and broken color front is apparent in the center of the CZCS image. The oceanographic boundary defined by the color front marks an area of high fishing activity and large mean

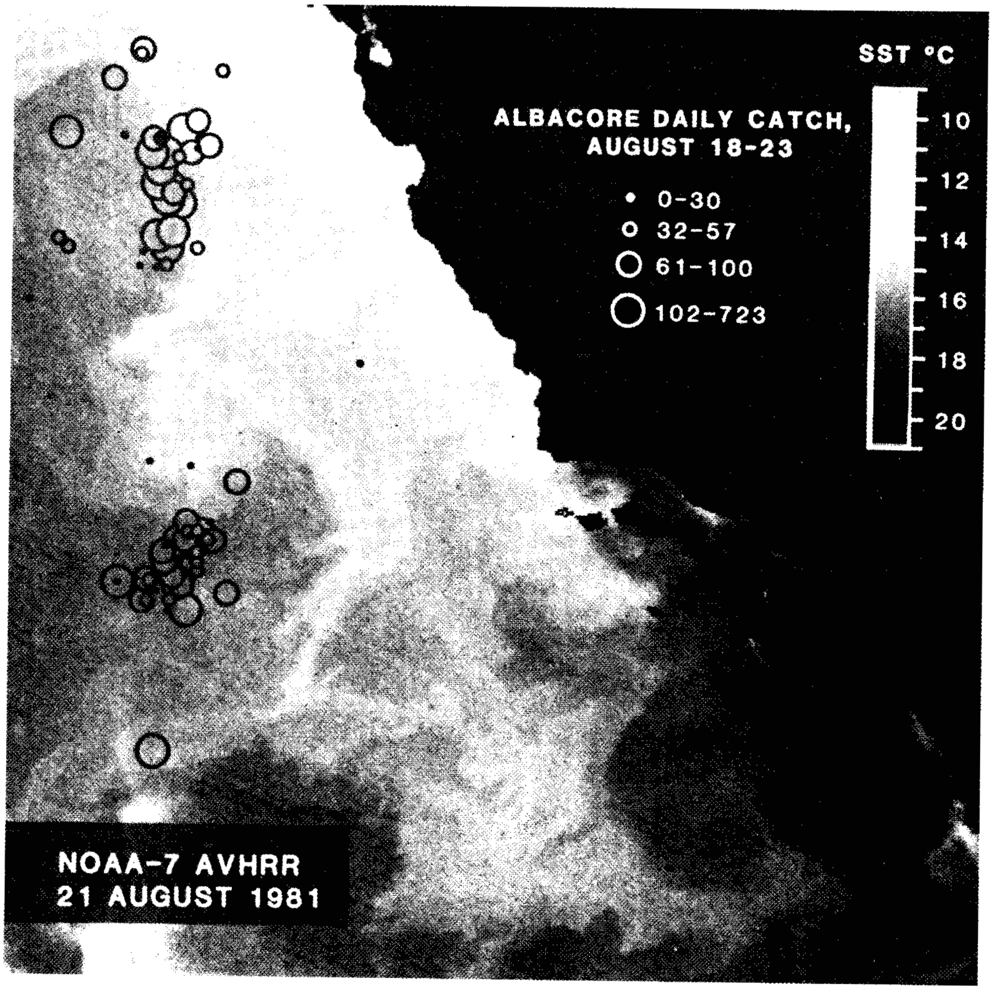
SST °C
ALBACORE DAILY CATCH,
AUGUST 18-23
● 0-30
○ 32-57
○ 61-100
○ 102-723
10
12
14
16
18
20
NOAA-7 AVHRR
21 AUGUST 1981

Fig. 3(a)

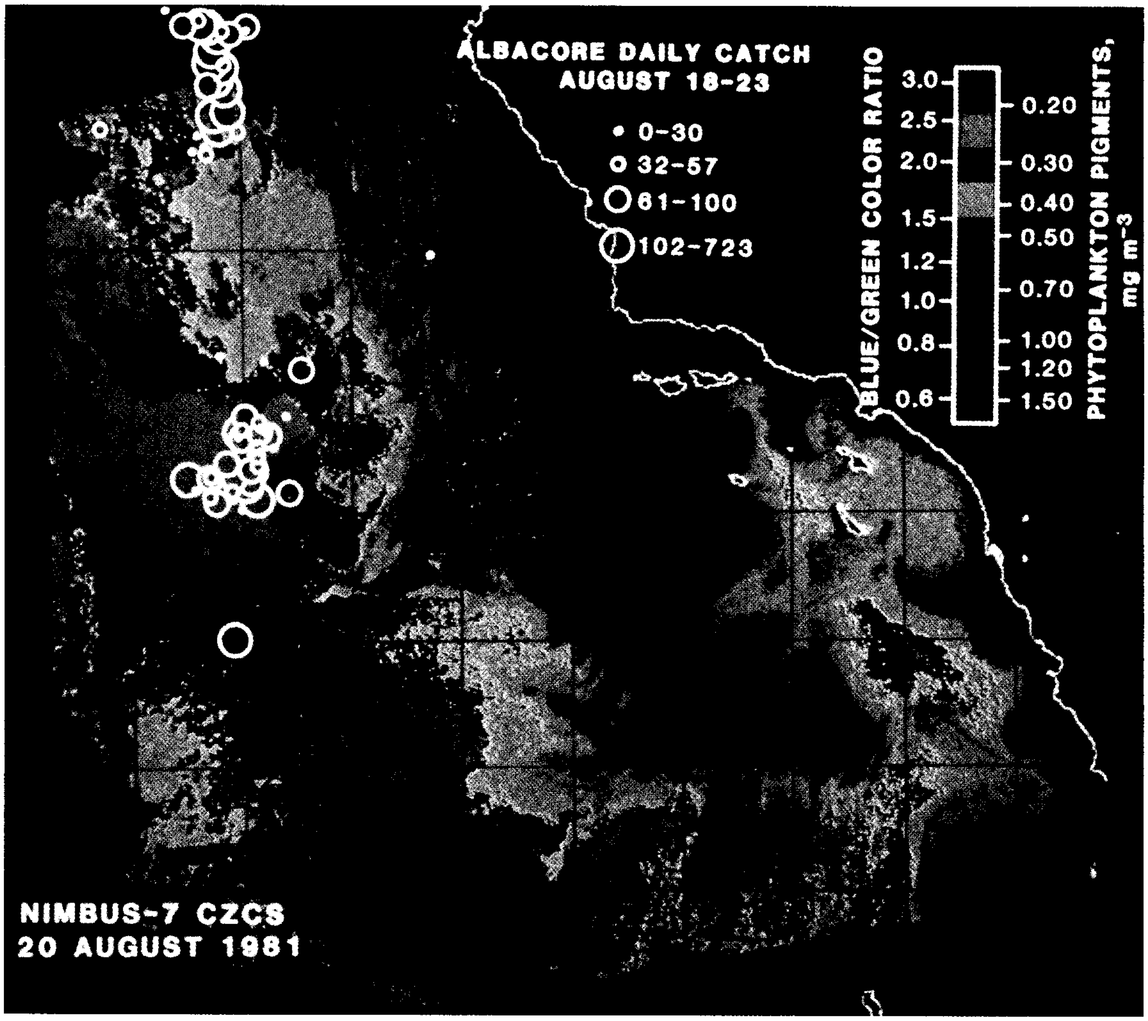

Fig. 3. Southern California daily albacore catches, 18 to 23 August 1981. (a) NOAA-7 AVHRR sea surface temperature, 21 August 1981, 0436 PST. (b) Nimbus-7 CZCS blue:green color ratio and phytoplankton pigment concentration, 20 August 1981, 1114 PST.

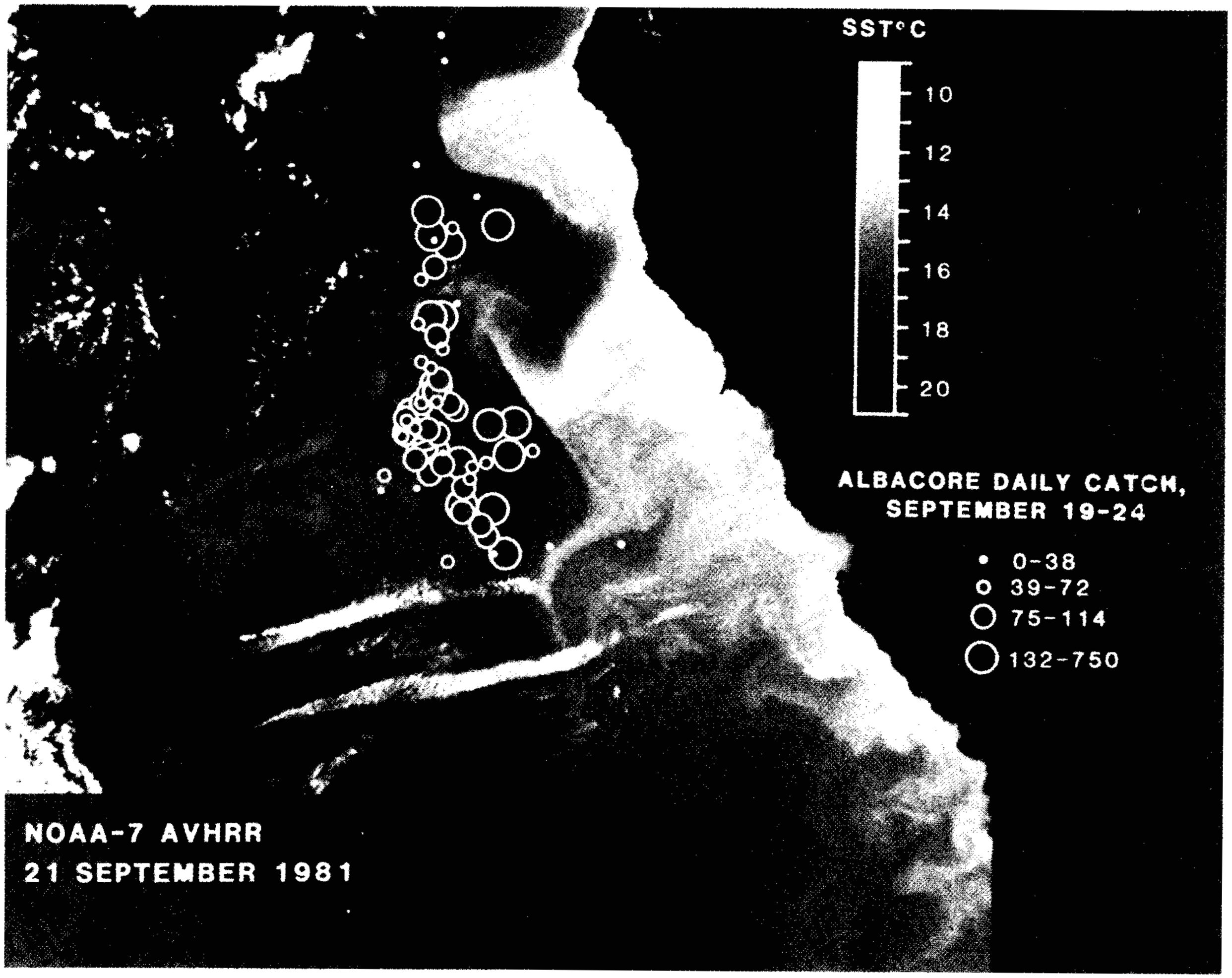
SST°C
10
12
14
16
18
20
ALBACORE DAILY CATCH,
SEPTEMBER 19-24
• 0-38
○ 39-72
○ 75-114
○ 132-750
NOAA-7 AVHRR
21 SEPTEMBER 1981

Fig. 4(a)

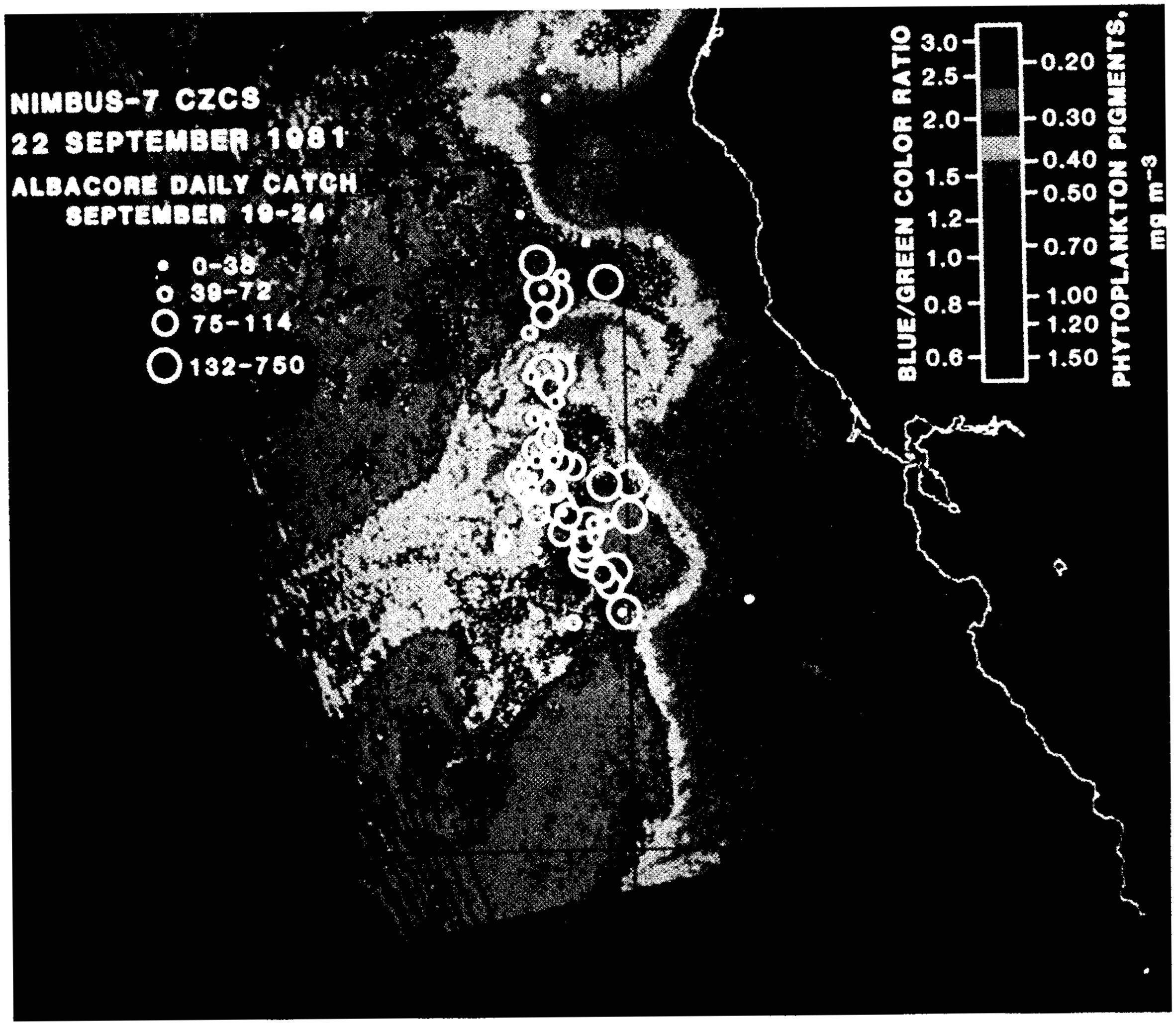

Fig. 4. Central California daily albacore catches, 19 to 24 September 1981. (a) NOAA-7 AVHRR sea surface temperature, 21 September 1981, 1403 PST. (b) Nimbus-7 CZCS blue : green color ratio and phytoplankton pigment concentration, 22 September 1981, 1104 PST.

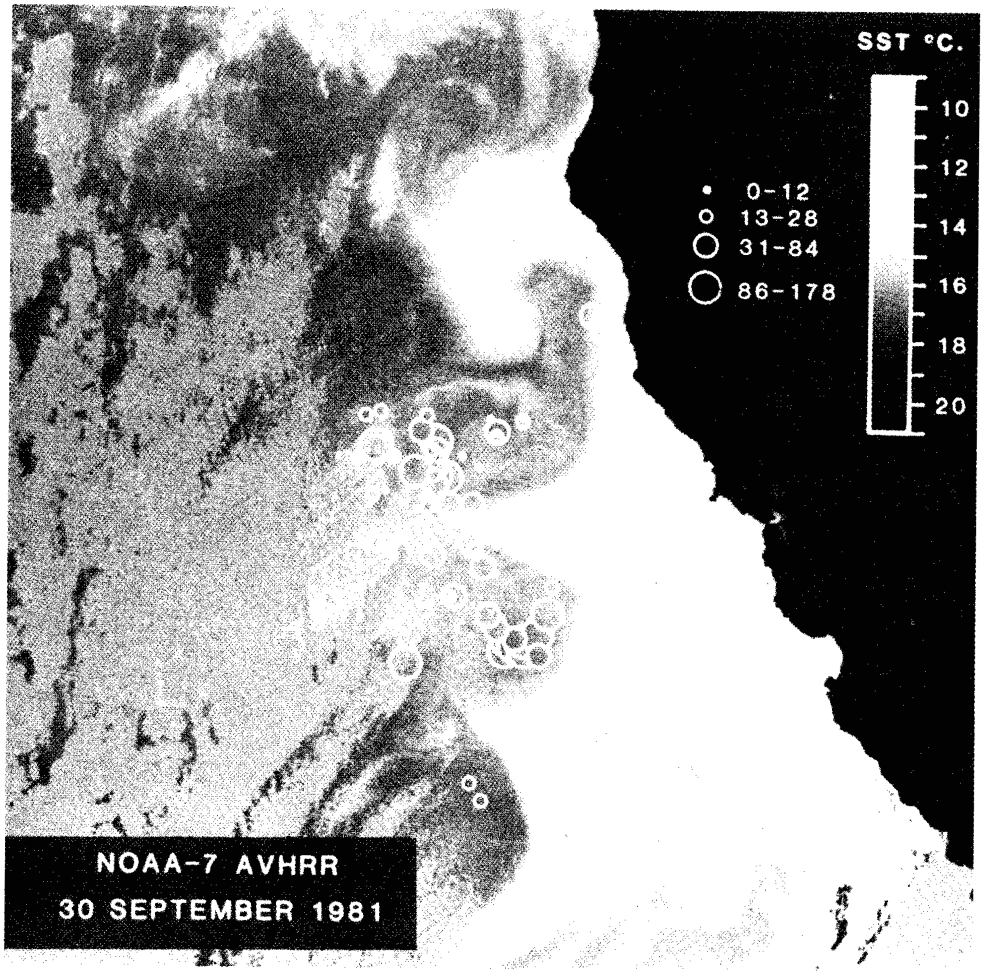
SST °C.
10
12
14
16
18
20
● 0-12
○ 13-28
○ 31-84
○ 86-178
NOAA-7 AVHRR
30 SEPTEMBER 1981

Fig. 5(a)

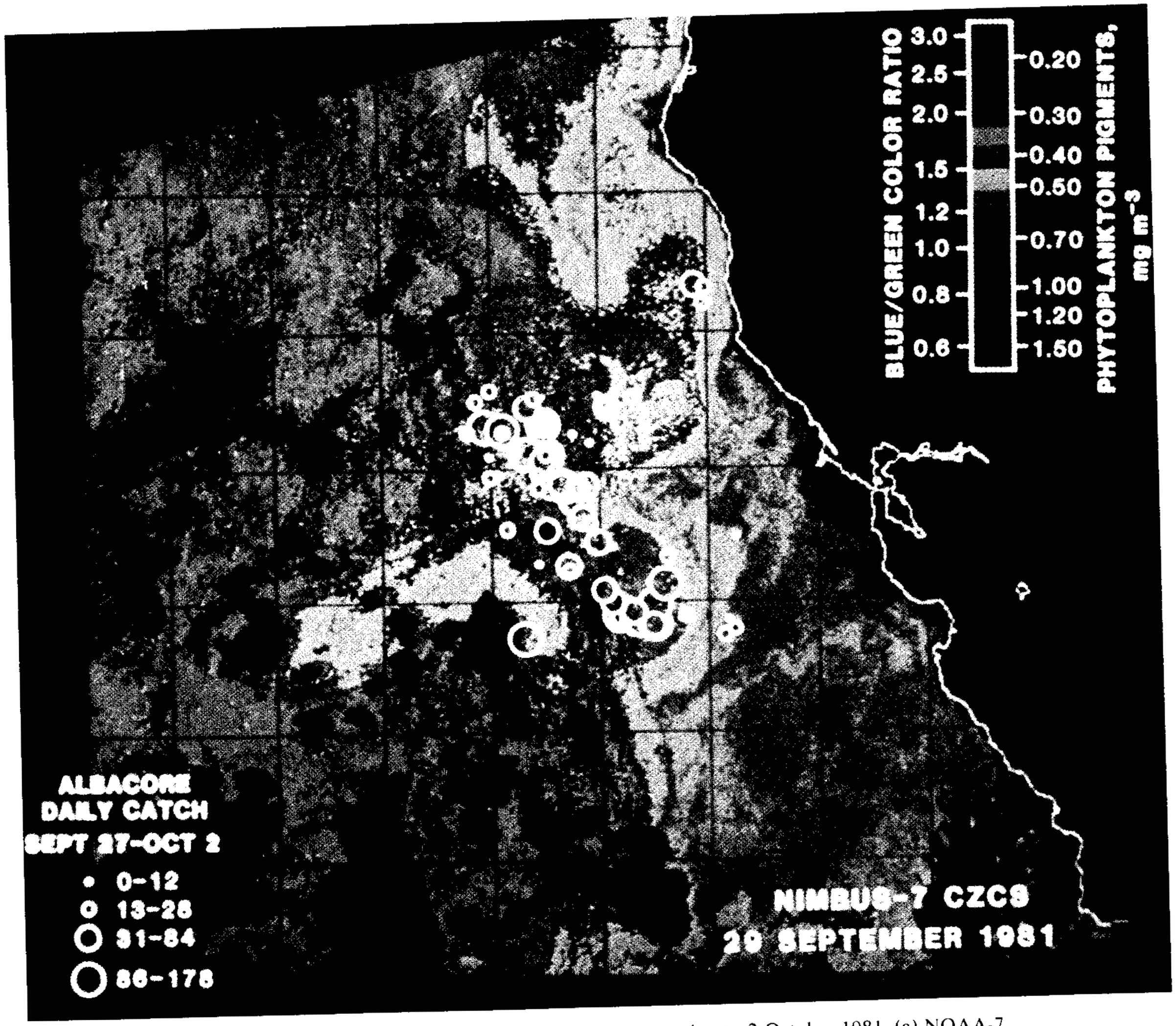

Fig. 5. Central California daily albacore catches, 27 September to 2 October 1981. (a) NOAA-7 AVHRR sea surface temperature, 30 September 1981, 1402 PST. (b) Nimbus-7 CZCS blue : green color ratio and phytoplankton pigment concentration, 29 September 1981, 1130 PST.


NOAA-7 AVHRR CH. 4
9 SEPTEMBER 1981
T SAT, °C
12
13
14
15
16
17
18
19
20
35° W
130° W
45° N
25
157
18
207
40
65
91
67
59
98
75
69
80
36
11
34
22
20
3
6
1
7
3
3
8
79
57
12
2
101
14
67
86
1
1

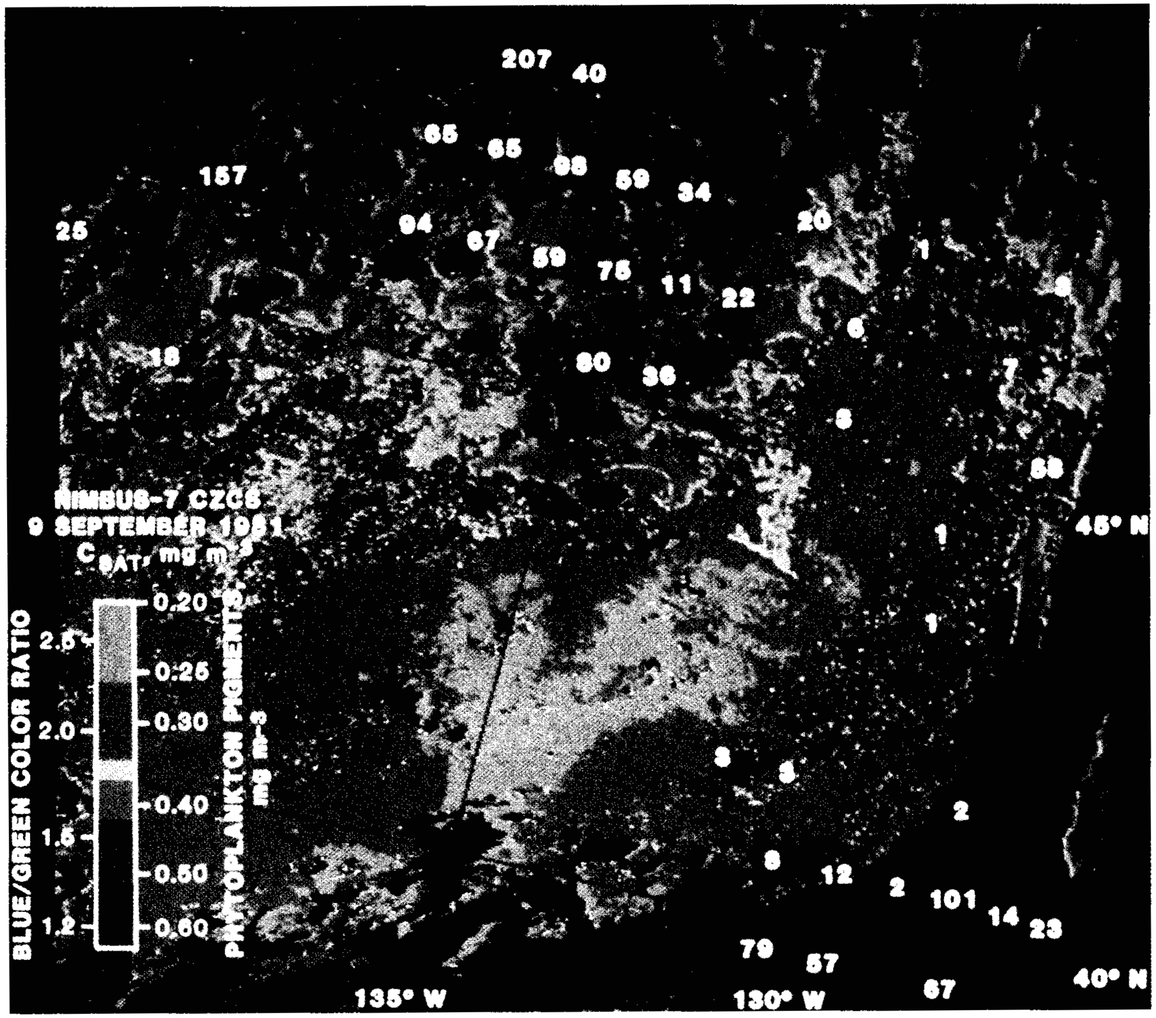

Fig. 6. Mean daily albacore catches in one-degree squares, 1 to 15 September 1981. (a) NOAA-7 AVHRR sea surface temperature, 9 September 1981, 1438 PST. (b) Nimbus-7 CZCS blue:green color ratio and phytoplankton pigment concentration, 9 September 1981, 1215 PST.

catches in relatively productive water. The concentration of fish in the lower right corner of the images, in a region obscured by clouds, was near the coast of northern California and most likely represents the same type of aggregation observed in the coastal images.

DISCUSSION AND CONCLUSIONS

The satellite images and concurrent albacore catch data clearly show that the distribution and availability of albacore are related to oceanic fronts. They also substantiate the conventional wisdom of many fishermen who use temperature or color 'breaks' to locate potentially productive fishing areas for albacore. Our results show that in nearshore regions commercially fishable aggregations of albacore are found in warm, blue oceanic waters near temperature and color fronts on the seaward edge of coastal water masses. Relatively intense fronts are favored, such as those associated with persistent upwelling (LAURS *et al.*, 1977). We have also demonstrated for the first time that shoreward intrusions of oceanic water are particularly favorable sites for albacore aggregation.

Our results also show that in offshore waters during late summer, commercial concentrations of albacore are associated with oceanic boundaries marked by color fronts detectable from satellites but without sea surface temperature gradients. The availability of albacore in offshore waters appears to be higher in relatively productive waters. The temperature characteristic denoting the boundaries of the relatively more productive waters, if present earlier, may be lost due to seasonal warming. However, the color gradient pattern is conserved.

Explanations for the environmental preferences of albacore are changing as new knowledge is acquired. Past studies stressed confinement to a physiologically optimum temperature range (THOMPSON, 1917; SUND *et al.*, 1981) or utilization of frontal gradients for thermoregulation (NEILL, 1976). However, temperature by itself cannot explain the observed distributions. Recent evidence based on acoustic tracking experiments conducted in conjunction with vertical temperature measurements shows that albacore move vertically through the thermocline and experience temperature changes of 5°C or more in 10 to 30-min periods (LAURS, 1983).

Albacore are believed to migrate to exploit the high densities of food organisms available in North American coastal waters. Albacore are opportunistic carnivores and consume northern anchovy, saury, euphausiids, squid, and decapod shrimp off California (PINKAS *et al.*, 1971). Suboptimum temperatures may limit them to the edges of the productive coastal water mass where such organisms are most abundant. BLACKBURN (1969) showed that both water temperature >20°C and abundance of suitable food are necessary conditions for the aggregation of yellowfin and skipjack tunas off Baja California. Like all tunas, the albacore is a visual predator (MAGNUSON, 1963). The aggregation of albacore in clear water on the oceanic side of fronts in nearshore areas may reflect an inability to efficiently capture large, mobile prey in turbid coastal water (MURPHY, 1959) and a dependence on food that has migrated or been dispersed across the coastal-oceanic boundary. In offshore regions, the aggregation of albacore in relatively productive waters presumably occurs because relatively higher amounts of food organisms are present, yet the waters are clear enough for the albacore to detect them.

We have shown that both i.r. and visible color data from satellites can define environmental limits on the spatial distribution of fishable aggregations of albacore and can do so more effectively than ship or aircraft data as used in the past. Satellite images readily resolve oceanic features with dimensions of scale >100 km; no other observational perspective so convincingly reveals the shapes, sizes, and continuity of such features. Phytoplankton pigment concentration or turbidity must be at least as important as temperature in explaining and predicting the seasonal migration of albacore to the North American coast for feeding and their local aggregation near productive waters. The oceanic images covering the offshore fishery later in the season illustrate a case in which sea surface temperature patterns cannot explain the catch distribution. While the CZCS image clearly shows an important color boundary, surface temperature gradients are nonexistent after the onset of seasonal warming. With the present results, we cannot rule out the possibility that subsurface temperature gradients may be associated with such surface color features. The continued presence of a color scanner in space is critical to the further development and use of such information in fisheries research, management, and exploitation.

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