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Tuna aggregation and feeding near fronts observed in satellite imagery

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Abstract— Stomach contents of albacore (*Thunnus alalunga*) and skipjack (*Katsuwonus pelamis*) caught off California in August 1983 showed they were feeding on juvenile northern anchovy (*Engraulis mordax*), other fishes, and planktonic crustaceans. The distribution and diet of these predators were related to mesoscale frontal features visible in satellite sea surface temperature and phytoplankton pigment imagery. Albacore were caught in the vicinity of a filament of cold, pigment-rich surface water that varied with the intensity of coastal upwelling on time scales of several days. Stomachs of albacore caught closer to the filament contained relatively more juvenile anchovy and fewer pelagic red crabs (*Pleuroncodes planipes*). Skipjack were caught in warm water in the Southern California Bight, north of their normal range due to El Niño warming. They appeared to be feeding most successfully near the strong frontal boundary of a productive, cold water mass south of Pt. Conception, where dense patches of euphausiids were available. Both species were feeding near variable, mesoscale centers of high productivity where prey abundance may be enhanced.

INTRODUCTION

TUNAS are highly active foragers of fishes, squids, and large zooplankton. Their feeding behavior is a concern of fisheries scientists and managers because (1) predation is a major component of the natural mortality of their fish prey and may control recruitment in prey populations (ROTHSCHILD and FORNEY, 1979), and (2) migration and schooling behaviors involved in feeding affect the availability and catchability of tuna for important commercial and recreational fisheries.

LAURS *et al.* (1984) showed that albacore (*Thunnus alalunga*) aggregated along the coast near surface frontal boundaries associated with coastal upwelling. They speculated that the distribution of albacore in these waters was related to feeding activity. BERNARD *et al.* (1985) analysed stomach contents of albacore and skipjack (*Katsuwonus pelamis*) caught off central and southern California during August 1983. They found marked interspecific differences in feeding habits.

We re-examined the distribution of these tunas and variations in their feeding habits using the data set from the study of BERNARD *et al.* (1985), but on a smaller spatial scale at which satellite imagery reveals habitat variability. We hypothesized that active searching for aggregations of prey would result in differences in stomach contents associated with mesoscale environmental features that persist long enough to affect prey availability.

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METHODS

Albacore and skipjack were sampled by nearly continuous daytime trolling during cruise 166 of NOAA ship *David Starr Jordan*, 15 August–1 September 1983 (Fig. 1). Analysis of stomach contents is described in BERNARD *et al.* (1985). Stomachs were frozen aboard ship and returned to the lab where the contents were measured and rough-sorted. Northern anchovy were sorted from all other fish. These fish were not sorted further, although the presence of juvenile *Sebastes* spp. was noted.

Satellite data covering the California coast were received, archived, and processed at the Scripps Satellite Oceanography Facility (SSOF) of Scripps Institution of Oceanography in La Jolla, California. Daytime thermal infra-red data from channel 4 (11 μm) of the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA-7 satellite were corrected for the effect of thin low clouds, using channel 2 (0.7–1.1 μm) near-infrared data (GOWER, 1985). Visible radiance data from the Coastal Zone Color Scanner

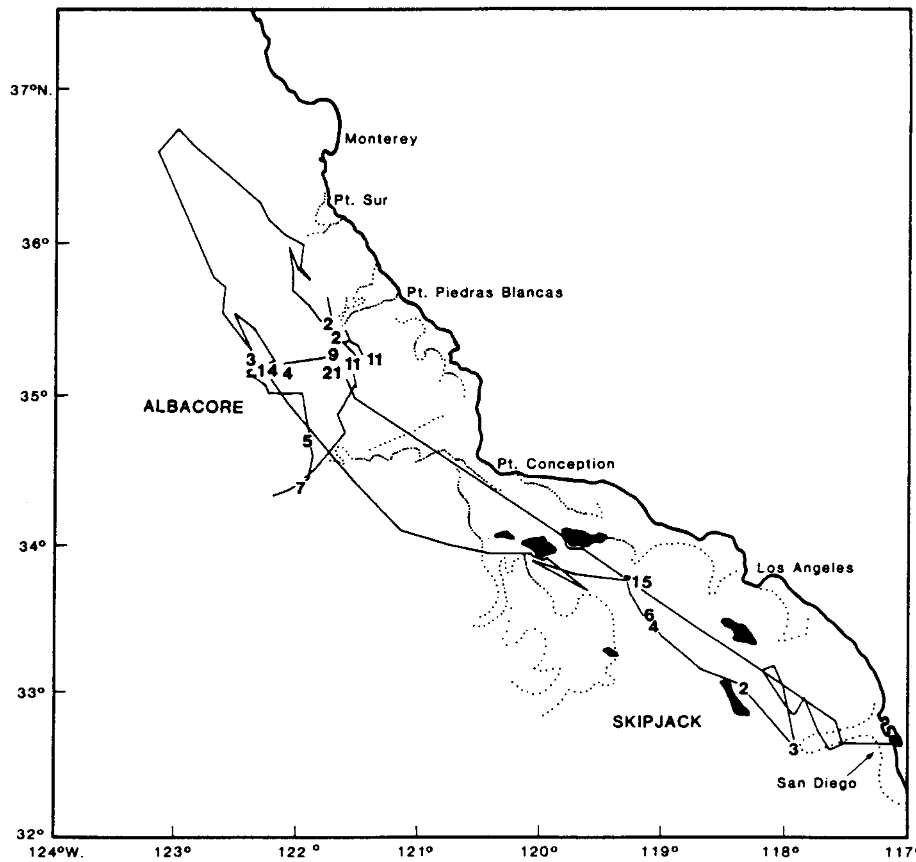

Fig. 1. Cruise track and catches of albacore (*Thunnus alalunga*) and skipjack (*Katsuwonus pelamis*) during cruise 166 of R.V. *David Starr Jordan*, 15 August–1 September 1983. Dotted line represents upwelling fronts visible in satellite imagery north of Pt. Conception on 25–26 August and south of Pt. Conception on 2 September.

(CZCS, on the Nimbus-7 satellite) were processed with an algorithm based on GORDON *et al.* (1983) to remove effects of Rayleigh and aerosol scattering and to derive pigment concentrations from corrected blue/green radiance ratios.

Spatial differences in predator and prey variables were tested by analysis of variance when possible. However, the highly skewed distributions of stomach content data required the use of the non-parametric Kruskal–Wallis test or, for variables with many zero values, chi-square contingency table analysis of differences between medians or frequencies of occurrence (CONOVER, 1971).

RESULTS

Albacore

Eighty-nine albacore were caught from 17 to 22 August in the vicinity of an upwelling filament at Pt. Piedras Blancas (Fig. 1). The series of AVHRR sea surface temperature images in Fig. 2 illustrates variability in the intensity of upwelling along the central California coast in response to changes in the strength of equatorward winds during August (Fig. 3).

On 4 August, coastal upwelling was well-developed following 15 days of strong upwelling-favorable winds (coastal upwelling index >100 m^3 s^{-1} 100 m^{-1}). The coldest surface water is near Pt. Sur, but a long filament of cold water extended offshore from Pt. Piedras Blancas. On 8 August, upwelling-favorable winds were strengthening following a brief lull and coastal upwelling was still well-developed. August 15 was the last of 4 days of relatively weak winds (coastal upwelling index <50). Coastal upwelling appeared weak in this image, but the sea surface temperature pattern was partially obscured by dense atmospheric water vapor.

August 23 was the first day in 13 with strong upwelling-favorable winds. Cold, upwelled water was visible along the coast at Pt. Piedras Blancas and to the north. By 25–26 August, after a brief pulse of strong winds, upwelling filaments were developing both at Pt. Piedras Blancas and at Pt. Sur. An anticyclonic eddy south of Pt. Piedras Blancas was entraining warm water from the Southern California Bight south of Pt.

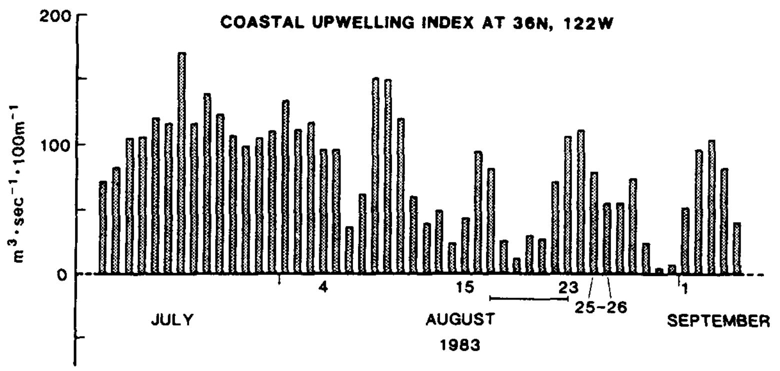

Fig. 3. Daily mean coastal upwelling indices, from alongshore winds in a 3° square centered at 36N, 122W (Pacific Fisheries Environmental Group, NOAA/NMFS/Southwest Fisheries Center, Monterey, California). Bar below abscissa indicates period of sampling north of Pt. Conception.

Conception. On 1 September, well-developed upwelling filaments were visible in spite of very weak winds over the previous 3 days.

During the period albacore were sampled, 15–22 August, equatorward winds and the surface pattern of cold, upwelled waters were not constant. Therefore, we grouped the sampled albacore by proximity to the upwelling filament at Pt. Piedras Blancas, based on the surface temperature where they were captured: near (16.5–17.0°C), intermediate (17.4–17.6°C), and far (18.1–18.3°C). Satellite-derived sea surface temperatures of the filament in Fig. 2 are 14–15.5°C.

Mean length and stomach volume of albacore increased with distance from the upwelling filament (Table 1). Eighty-two percent of the total number of prey items in albacore stomachs were fishes [35% juvenile anchovies of 22–47 mm SL and 47% other fish (BERNARD *et al.*, 1985)]. Stomach fullness and prey composition varied greatly between individuals. For example, stomach fullness ranged between 4 and 73%. Stomachs with identifiable food sometimes contained only prey of a single type (e.g. anchovies, other fish, or pelagic red crabs), but more often contained two or more prey types.

Neither mean stomach fullness nor median total prey per albacore varied significantly with proximity to the filament. However, there were significant differences in prey composition: the numerical proportion of fish in the diet increased with proximity to the filament, anchovy were relatively more numerous in the stomachs of albacore caught near the filament, other fish were more numerous in albacore caught at intermediate distances and temperatures, and pelagic red crabs were more numerous in the diet far from the filament. No other prey category exhibited significant differences in relative numerical importance.

Table 1. Albacore (Thunnus alalunga) *size and diet differences with distance from upwelling filament*

	Near	Intermediate	Far	
Means				
Fork length (cm)	65.7 ± 2.0	72.8 ± 2.7	75.1 ± 3.7	$P < 0.01$
Stomach volume (ml)	90.0 ± 12.9	135.8 ± 20.0	141.9 ± 25.0	$P < 0.01$
Stomach fullness	0.35 ± 0.04	0.37 ± 0.07	0.32 ± 0.07	NS
Medians				
Total prey	27	25	19	NS
Fish/total	0.98	0.91	0.86	$P < 0.05$
Anchovies/total	0.55	0.00	0.11	$P < 0.01$
Other fish/total	0.30	0.67	0.06	$P < 0.10$
Crustaceans/total	0.014	0.000	0.059	NS
Frequencies of occurrence				
Pleuroncodes planipes	0.03	0.17	0.33	$P < 0.01$
Amphipods	0.26	0.14	0.27	NS
Euphausiids	0.21	0.22	0.07	NS
Other crustaceans	0.87	0.83	0.93	NS
Cephalopods	0.26	0.47	0.33	NS

Differences in mean length, stomach volume, and stomach fullness (±2 S.E.) were tested by one-way analysis of variance, median total prey by Kruskal–Wallis test, median relative numbers of prey categories by the median test, and frequencies of occurrence of other prey types by chi-square contingency table analysis. n = 38 near the filament, 36 at intermediate distances, and 15 far from the filament.

NS = Not significant.

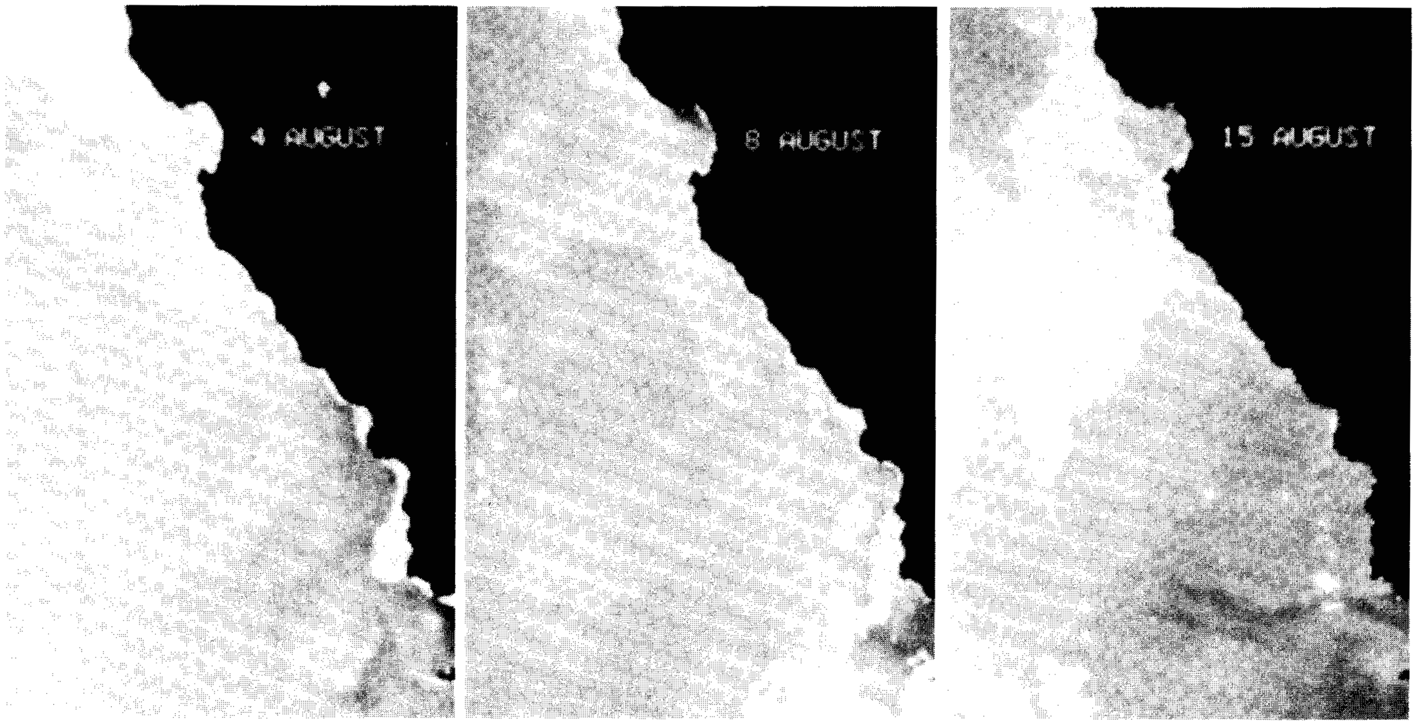

Fig. 2. Series of AVHRR sea surface temperature images of the central California coast during August 1983. In each image, Pt. Conception is at the lower right and Monterey Bay is near the top edge. Land is masked in black and clouds in white, with sea surface temperature increasing from light grey (~13°C) to dark grey (~18°C).

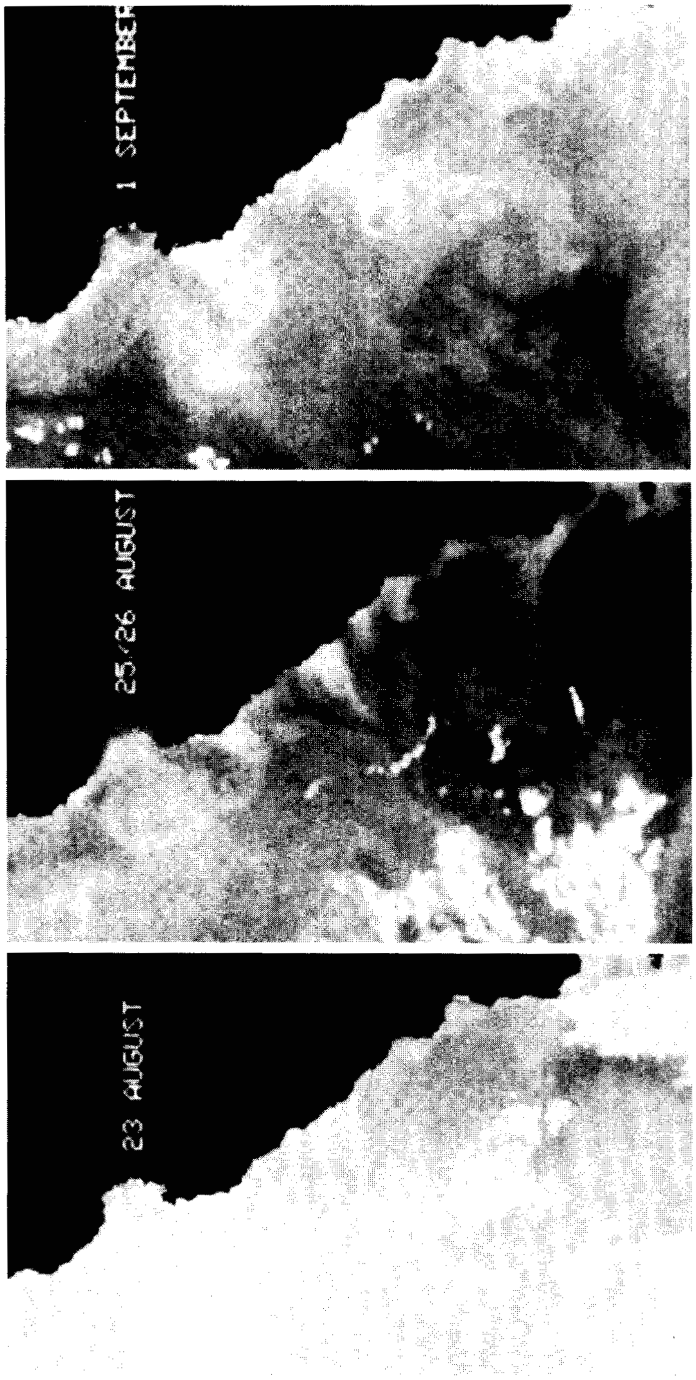
1 SEPTEMBER
25/26 AUGUST
23 AUGUST

Fig. 4. AVHRR image of the Southern California Bight from 2 September 1983, masked as in Fig. 2. Sea surface temperature ranges from 13.5°C (light grey) to 22°C (dark grey).

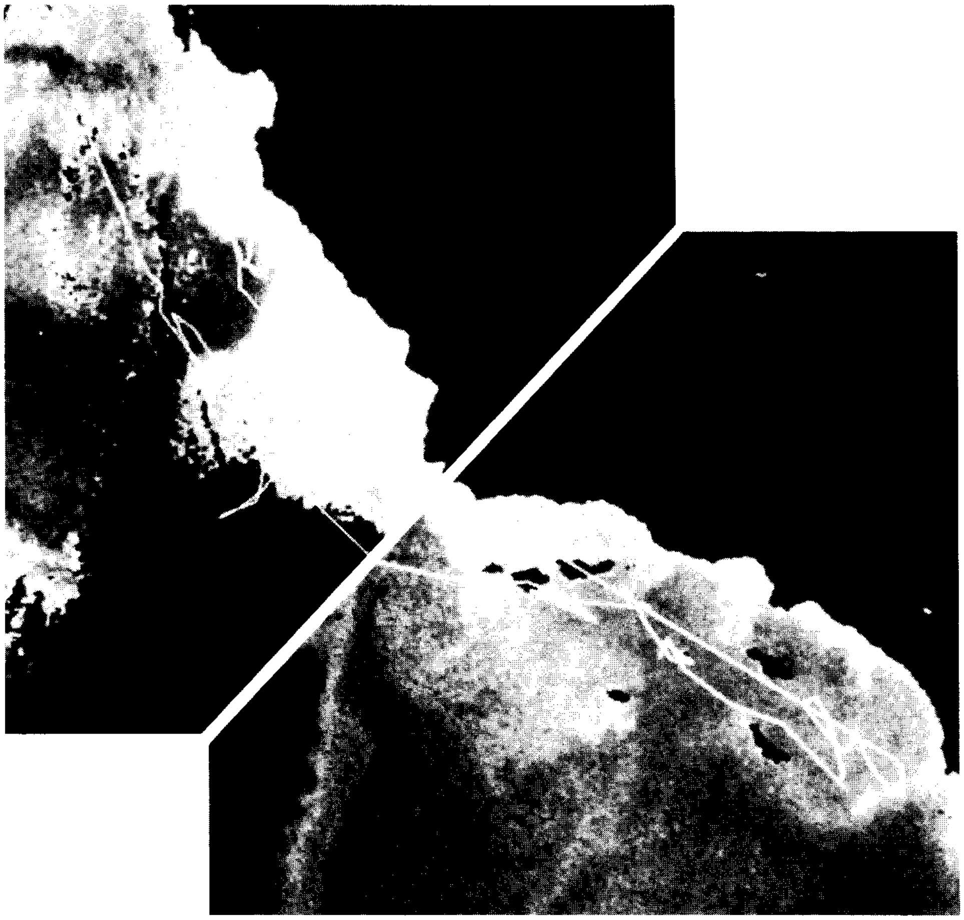

Fig. 5. CZCS images of central California (26 August 1983, top left) and Southern California Bight (2 September 1983, bottom right). Land and clouds are masked with black. Phytoplankton pigment concentrations range from 0.06 (dark grey) to 3.5 mg m $^{-3}$ (light grey).

Skipjack

In 1983, skipjack were caught in 20.9–22.4°C water in the Southern California Bight. Mean August surface temperatures in these waters are ≤18.5°C (Robinson, 1976). Skipjack were caught at two distinct sites (Fig. 1; temperature and pigment images in Figs 4 and 5). One group of 25 was captured near the edge of a consistently cool and productive water mass south of Pt. Conception. Another group of five was captured near a small upwelling squirt off San Diego (most obvious in the CZCS image, Fig. 5).

Eighty-six percent of the total number of prey items in skipjack stomachs were crustaceans, dominated by euphausiids (76%, primarily the coastal species *Nyctiphanes simplex*; Bernard *et al.*, 1985). The group of five caught near the weak upwelling squirt had a significantly greater proportion of empty stomachs (no identifiable prey items) than did the larger group (4 of 5 vs 6 of 25, $P < 0.25$, chi-square contingency table). We could not extend the comparison of food habits any further with one group containing only one stomach with identifiable prey.

DISCUSSION

Several aspects of the stomach content data examined by Bernard *et al.* (1985) may be interpreted as the result of "opportunistic" feeding. Exotic prey species, notably pelagic red crabs and the euphausiid *Nyctiphanes simplex*, were exploited as they became available off California during the anomalously warm summer of 1983. In that study and other studies of albacore feeding in the eastern North Pacific, diet composition varies both geographically and from year to year. Finally, the extreme non-randomness of counts of individual prey species in stomachs suggests exploitation of dense patches of prey.

The CZCS images in Fig. 5 illustrate that the cold, upwelled waters along the central California coast in Fig. 2 and to the south of Pt. Conception in Fig. 4 are rich in phytoplankton. The temperature fronts near which tunas were captured are also color fronts, or strong gradients in phytoplankton pigment concentration. This correspondence of temperature and color fronts is generally true of California coastal waters during the summer upwelling season. The productivity of the coastal water mass presumably supports an enhanced production at higher trophic levels, including prey populations exploited by tunas.

The diet of albacore caught nearest the upwelling filament at Pt. Piedras Blancas may reflect high availability of juvenile anchovy at that site. Juveniles are generally found close to shore in water <100 m (Messersmith *et al.*, 1969). This is inshore of the center of distribution of anchovy larvae (Hewitt, 1980). Albacore may have been sampling the cohort spawned in February–April as it moved onshore in late August. It is conceivable that offshore flow in the surface layer (upwelling) caused an accumulation of shoreward-moving anchovies. The pelagic red crabs consumed by albacore in warmer water far from the upwelling filament are rarely found this far north. The albacore were able to exploit this prey resource that had become available by a range extension during El Niño.

Skipjack are tropical tunas not normally found off California. During El Niño, their range expanded into the anomalously warm surface waters of the Southern California Bight. Blackburn (1969) found that skipjack off southern Baja California aggregated in waters warmer than 20°C where suitable food was abundant. During active upwelling, they aggregated at the edges of cool, high-chlorophyll areas where their principal prey, pelagic red crabs, were most abundant. The diet of the skipjack we sampled was also dominated by crustaceans, but by the euphausiid *Nyctiphanes simplex* rather than pelagic red crabs.

If the skipjack we sampled were aggregating to feed, their differential feeding success suggests that more of them had aggregated at the most favorable feeding site. Presumably, more prey were available near the consistently productive water mass off Pt. Conception than near the small upwelling squirt to the south.

Nyctiphanes simplex is a warm-water, coastal euphausiid. Point Conception is normally the northern limit of its range, with greatest abundances off southern Baja California (Brinton, 1981). The range of *Nyctiphanes* had extended north at least to Monterey during zooplankton sampling along the coast of California on California Cooperative Oceanic Fisheries Investigations (CalCOFI) cruises in December 1983 and early 1984 (E. Brinton, personal communication). In fact, *Nyctiphanes* was the most common euphausiid prey of juvenile coho salmon (*Oncorhynchus kisutch*) off Washington and Oregon during summer 1983 (Pearcy *et al.*, 1985), indicating a range extension of more than 1500 km. In the December 1983 CalCOFI samples, greatest abundances were observed along sampling lines in the vicinity of the Channel Islands, south of Pt. Conception in the Southern California Bight, where *Nyctiphanes* had been found in skipjack stomachs in late August.

Off Baja California, large numbers of *N. simplex* are often found in 13–14°C upwelled water near the coast (E. Brinton, personal communication). This was the temperature of upwelled water in the Southern California Bight during El Niño. Large surface swarms have been observed during daylight off Baja California; this species exhibits little or no diurnal vertical migration. Therefore, it is likely that the skipjack found near the cold, productive waters in the vicinity of the Channel Islands were feeding on dense swarms of *Nyctiphanes*.

CONCLUSION

By using satellite imagery to reveal mesoscale habitat variability, we have documented two examples of feeding aggregations associated with oceanic fronts. Albacore aggregated to feed near a variable upwelling center of high productivity. Their diet was influenced by changes in prey availability with distance from this filament. Skipjack aggregated and fed most successfully near cool, productive waters where prey availability was high.

Both of these species had migrated to California coastal waters in the summer of 1983. Albacore migrate seasonally across the Pacific and exploit dense prey populations in the California Current during summer upwelling; skipjack had migrated to the Southern California Bight in response to anomalously warm surface temperatures during El Niño. Our observations demonstrate that aggregation at mesoscale coastal features of high productivity and prey availability is part of the feeding strategy of albacore and skipjack. The use of satellite temperature and color imagery to locate fishable aggregations of tunas is based on this feeding behavior.

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