# SMALL-SCALE MOVEMENTS OF ALBACORE, *THUNNUS ALALUNGA*, IN RELATION TO OCEAN FEATURES AS INDICATED BY ULTRASONIC TRACKING AND OCEANOGRAPHIC SAMPLING

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## ABSTRACT

Studies with ultrasonic tracking techniques and oceanographic sampling demonstrated that oceanographic conditions play an important role in the local concentrations and movements of albacore, *Thunnus alalunga*, in U.S. coastal waters. Albacore show a tendency to congregate in the vicinity of coastal upwelling fronts, presumably to feed. They move away from the immediate area when upwelling ceases and the upwelling front is no longer present at the surface. The movements of albacore also appear to be related to the distribution of sea surface temperature, with fish spending little time in water with surface temperatures cooler than 15.0°C.

The average swimming speed for three fish tracked between 27.8 and 50 h was 1.6 knots (82.4 cm/s) with each fish exhibiting slightly faster swimming speeds during hours of daylight than during hours of darkness.

The albacore, *Thunnus alalunga* (Bonnaterre), is widely distributed in the Pacific Ocean. The single subpopulation which is found in the North Pacific (Otsu 1960) supports important surface commercial fisheries in coastal waters off North America and Japan and subsurface fisheries in the central temperate Pacific. The species is also highly prized by U.S. recreational fishermen. Passive tagging methods have been used to study large-scale migratory patterns of albacore in the North Pacific (Ganssle and Clemens 1953; Otsu 1960; Clemens 1961, 1963; Otsu and Uchida 1963; Laurs and Nishimoto[4]); however, information on small-scale movements is scant.

In order to examine the small-scale movements of schools of albacore and evaluate the effects that oceanographic conditions may have on the local concentrations and movements of albacore in coastal waters off the United States, studies were conducted with ultrasonic tracking techniques and oceanographic sampling.

Tracking the movements of animals to which ultrasonic transmitters have been attached is a technique that has been developed over the past two decades. This valuable technique has gained such wide application in recent studies of marine fishes and crustacea that it is more convenient to cite a bibliographic source (Stasko 1975) than to cite individual references.

## METHODS

In the course of acoustic tracking studies, environmental data commonly have been collected for correlation with observed movements of the animal. At times, small auxiliary craft have been used for this purpose in support of the vessel doing the tracking, but usually the collection of environmental data has been done entirely from aboard the tracking vessel, necessarily limiting measurements to the ship's track. This study represents a significant expansion of supportive environmental data acquisition: for the first time a major oceanographic research vessel and an aircraft were coordinated with acoustic tracking of fish. The ultrasonic tracking experiment involved the use of the commercial albacore fishing baitboat *Linda* on charter to the American Fishermen's Research Foundation, the National Marine Fisheries Service (NMFS) RV *David Starr Jordan,* and a Coast Guard aircraft equipped with sea surface temperature measuring equipment.

### Capture, Handling, and Tagging of Albacore

The capture of fish, tagging with ultrasonic

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[4]Laurs, R. M., and R. N. Nishimoto. 1974. Joint NMFS-AFRF albacore tagging study. SWFC Admin. Rep. LJ-74-47:63-81.

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transmitters, and tracking of the fish were done aboard *Linda* by three NMFS scientists with assistance from the crew of *Linda*. Albacore ranging in size from 74 to 87 cm fork length with estimated weights of 8.2 to 13.6 kg were caught on hook and line baited with anchovy. The fish was played an average of 5 min before being brought on board by dip net. Without removing it from the net, the fish to be tagged was placed on its side on a plastic covered foam measuring pad on the deck where it was measured to the nearest lower centimeter and the transmitter was attached. A wet burlap bag was placed over its head to keep the fish calm. No anesthetic was used.

The ultrasonic transmitter was attached to the back of the fish, immediately in front of the second dorsal fin, with two sutures through the skin and muscle tissue in that area. Upon completion of tagging, fish were immediately replaced in the water. Total elapsed time for fish out of water was between 1 and 1½ min. Within 2 to 4 s after being released, each tagged fish was observed righting itself and actively swimming downward and out of sight. One fish was tracked at a time. The three fish tracked longer than 24 h were tagged in the manner described above. Several fish tracked for shorter periods early in the cruise were tagged by inserting the transmitter into the stomach through the mouth. This latter method was abandoned when it appeared that acoustic signal attenuation caused by internal implacement was resulting in an inadequate receiving range.

## Tracking Equipment

The transmitter tags and hydrophone used were built by the Northwest and Alaska Fisheries Center, Seattle, Wash. The tags were cylindrical measuring 8.2 by 1.9 cm, weighing 67 g in air and 43 g in water, and emitted a 45 or 50 kHz signal at a pulse rate of 120 pulses/min. Acoustic source level of the tag was 63 dB (reference to 1 $\mu$bar at 1 m in fresh water).

The hydrophone was a tuned 6-element array (sensitivity - 69 dB, reference to 1 $\mu$bar at 1 m) with a beam width of 20° horizontally and 40° vertically at the 3-dB point. This was attached to the lower end of a 3-cm aluminum pipe, bracketed to the starboard rail amidship of the tracking vessel. A geared electric motor at the top of the pipe rotated the hydrophone, which was remotely controlled from the tracking station in the wheelhouse. Signals picked up by the hydrophone were fed into a Lawson VLF-1[5] superheterodyne receiver.

## Tracking Procedure

With the hydrophone remote-control unit installed in the pilothouse of *Linda* alongside the engine and steering controls and the receiver placed about 2 m away, one person was able to operate the tracking system and control the vessel simultaneously. Directing the hydrophone for maximum signal, the operator moved the vessel on that heading until satisfied, on a basis of signal strength, with his proximity to the fish. The receiving range varied widely according to sea state, but on the average *Linda* was kept an estimated 500 m from the tagged fish. The fish moved continuously and so, consequently, did the vessel, but vessel speed of more than 2 knots was seldom necessary to keep up with the fish. Position of the tracking vessel was determined approximately once an hour and was taken also to represent the position of the fish at that time. Most of the navigation for *Linda* was done by the nearby *David Starr Jordan*, with a combination of Loran, radar, and Omega systems.

## Oceanographic Observations Made From Ship

Detailed oceanographic observations were made aboard *David Starr Jordan* in support of the ultrasonic tracking experiments. These included continuous monitoring of surface temperature and salinity and measurements of subsurface temperature and salinity at selected stations. Observations were also made to evaluate biological factors of the marine environment. These included continuous monitoring at the surface and subsurface measurements at selected stations of chlorophyll a by fluorometric techniques (Holm-Hansen et al. 1965), measurements of primary productivity by $^{14}C$ methods (Owen and Zeitzschel 1970), and estimates of the standing stocks of potential albacore food organisms.

The estimates of potential albacore forage were derived from hauls made with a 1.8-m Isaacs-Kidd midwater trawl (IKMT) lined with a 58-mm mesh. The hauls were taken during hours of darkness

[5]Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

from the surface to a depth of approximately 175 m at a ship speed of about 5 knots. The volumes of water strained were estimated from data obtained by a TSK[6] depth-distance recorder mounted in the mouth of the trawl. The Formalin-preserved IKMT catches were sorted into several categories of fishes, cephalopods, crustaceans, and other animals, and the displacement volume of each of these kinds of animals was measured and standardized in ml/1,000 $m^3$ of water filtered for each haul. The standardized values of 1) larval and juvenile fishes, 2) epipelagic fishes, 3) cephalopods, and 4) crustaceans were summed for each haul and collectively regarded as potential albacore forage. Analysis of stomach contents of albacore has shown that these categories of organisms are important in the diet of albacore (Pinkas et al. 1971) in this area.

## Oceanographic Observations Made by Aircraft

A Coast Guard aircraft equipped with a Barnes PRT-5 infrared radiometer made measurements of sea surface temperature for evaluation of the small-scale features and changes in the distribution of sea surface temperature.

## RESULTS AND DISCUSSION

Six albacore were tagged and tracked with ultrasonic equipment for periods ranging from about 2 to 50 h and distances ranging from 6.5 to 150.7 km (3.5 to 81.3 nmi). Results will be presented for fish numbers 4, 5, and 6, which were tracked for 27.8, 41.4, and 50.0 h, respectively. There are too few data for discussion for fish numbers 1, 2, and 3 because of the short periods that the fish were tracked. A summary of the tracking date and time, tagging location, distance tracked, and fork length of fish for fish numbers 4, 5, and 6 is given in Table 1.

Tagged fish rejoined untagged albacore after being returned to the water, and tended to remain in their company. Surface "boils" characteristic of albacore were frequently sighted close by *Linda*, and approximately 30 fish of the same general size as fish tagged with ultrasonic transmitters were caught by the crew while tracking was in progress. Also, one tagged fish "lost" the previous day was heard intermittently over a 4-h period during the track that followed. We were able to distinguish between the two fish because of slightly different signals from the tags.

[6]Tsurumi Seiki Kosakusho Co., Ltd., Yokohama, Japan.

TABLE 1.—Summary of tracking date and time, fork length of albacore, location of tagging, and distance tracked.

| No. | Date | Time | Fork length | Tagging location Lat. | Long. | Distance |
|---|---|---|---|---|---|---|
| 4 | 8-16-72 to 8-17-72 | 1445 to 1845 | 84 cm | 36°49.8′N, | 122°19.1′W | 41.6 nmi (77.1 km) |
| 5 | 8-19-72 to 8-20-72 | 0715 to 2345 | 87 cm | 36°50.3′N, | 122°13.6′W | 61.4 nmi (113.8 km) |
| 6 | 8-25-72 to 8-27-72 | 1000 to 1205 | 85 cm | 35°20.0′N, | 121°22.0′W | 81.3 nmi (150.7 km) |

## Speed of Albacore Movements

Swimming speeds for albacore were estimated from straight-line calculations using position of the tracking vessel. The average swimming speed, based on the total distance and time that the fish were tracked, for fish numbers 4, 5, and 6 was about 1.6 knots (82 cm/s). Speeds calculated from hourly ship positions for each fish ranged from 0.1 to 3.6 knots (5 to 185 cm/s). Table 2 shows the percentage of time each fish spent at various swimming speeds. There were day-night differences in the rate of movement, with fish exhibiting faster swimming speeds during hours of daylight (0500 to 1900 h) than during hours of darkness. The average speed during daylight for fish numbers 4 and 5 was 1.7 knots (88 cm/s) and for number 6 was 2.1 knots (108 cm/s). The average speed during nighttime for fish numbers 4 and 6 was 1.3 knots (67 cm/s) and for fish number 5 was 1.0 knot (51 cm/s). Table 3 gives a summary of time, distance, and mean speeds.

Moonlight also appeared to influence the rate of movement of fish number 5. This fish, which had been moving steadily at about 2.0 knots (103 cm/s) for about 3 h after moonrise and following a course about 20° west of the full moon, came to a near stop

TABLE 2.—Percent of time each albacore spent at various swimming speeds.

| Speed | | Fish no. 4 | Fish no. 5 | Fish no. 6 |
|---|---|---|---|---|
| knots | cm/sec | | Percent | |
| <0.5 | <26 | 8.0 | 5.9 | 0.0 |
| 0.5-0.9 | 26- 46 | 12.0 | 23.5 | 15.8 |
| 1.0-1.4 | 51- 72 | 32.0 | 35.3 | 28.9 |
| 1.5-1.9 | 77- 98 | 24.0 | 11.8 | 15.8 |
| 2.0-2.4 | 103-124 | 16.0 | 17.6 | 28.9 |
| 2.5-2.9 | 129-149 | 4.0 | 2.9 | 0.0 |
| 3.0-3.4 | 154-175 | 0.0 | 2.9 | 10.5 |
| >3.5 | >175 | 4.0 | 0.0 | 0.0 |

TABLE 3.—Summary of duration and distance tracked and mean speed of albacore tracked with ultrasonic transmitters.

| Item | Fish no. 4 | Fish no. 5 | Fish no. 6 |
|---|---|---|---|
| Time tracked (h) | 27.8 | 41.4 | 50.0 |
| Distance tracked: | | | |
| nmi | 41.6 | 61.4 | 81.3 |
| km | 77.1 | 113.8 | 150.7 |
| Mean speed: | | | |
| knots | 1.6 | 1.5 | 1.6 |
| cm/s | 82 | 77 | 82 |
| bl/s[1] | 0.98 | 0.88 | 0.96 |
| Mean speed, day:[2] | | | |
| knots | 1.7 | 1.7 | 2.1 |
| cm/s | 88 | 88 | 108 |
| bl/s[1] | 1.05 | 1.01 | 1.27 |
| Mean speed, night:[3] | | | |
| knots | 1.3 | 1.0 | 1.3 |
| cm/s | 67 | 51 | 67 |
| bl/s[1] | 0.80 | 0.59 | 0.79 |

[1]bl/s = body lengths per second.
[2]0500-1900 h.
[3]1900-0500 h.

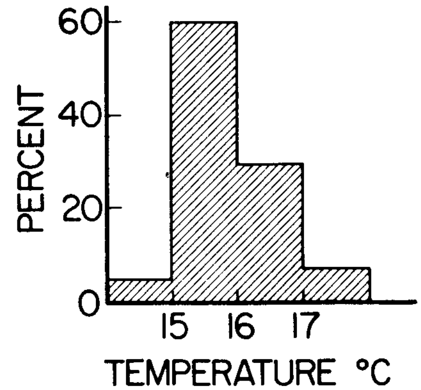


FIGURE 1.—Percent of time (hours) spent in waters of various sea surface temperature by albacore numbers 4, 5, and 6.

for nearly an hour when the moon was suddenly obscured by dense fog at about 0300 h.

The mean swimming speeds calculated from the tracking experiment are close to estimates of swimming speed derived from passive tagging results. For example, based on data given in the Japanese Fisheries Agency (1975) report, two tagged albacore, which were released in the western North Pacific and recovered in the eastern North Pacific about 3½ mo later, traveled at 1.1 knots (57 cm/s), assuming they followed a great circle route and were caught the day they arrived at the recovery location. The mean swimming speeds found in this study are slightly less than twice the calculated minimum swimming speed necessary for an 80-cm albacore to maintain hydrostatic equilibrium (Dotson 1977).

## Relationship of Albacore Movements to Sea Surface Temperature

The movements of the fish tagged with ultrasonic transmitters appeared to be influenced by the distribution of sea surface temperature. Figure 1 shows the percentage of the time that fish numbers 4, 5, and 6 spent in waters of various surface temperatures. Fish number 6 spent no time in water with surface temperatures less than 15.0°C although roughly 20% of the waters 5 nmi distant on both sides of the path followed by the fish were colder than 15.0°C. Fish number 4 was in water which had surface temperatures colder than 15.0°C 12.5% of the time, while 35% of the waters 5 nmi distant on both sides of the path followed by the fish was colder than 15.0°C. Fish number 6 was in water with surface temperatures warmer than 17.0°C 22% of the time, which coincided with the percentage of area with temperatures greater than 17.0°C. Water with temperature higher than 17.0°C was not available to fish numbers 4 and 5.

These results indicate that the transmitter-tagged fish spent very little time in water with surface temperatures less than 15.0°C. This is especially evident when charts showing the tracks followed by the fish and the contoured field of sea surface temperature observed by *David Starr Jordan* at the time of tracking are examined. Figures 2, 3, and 4 show tracks followed by fish numbers 4, 5, and 6, respectively, and sea surface temperature. In these figures, temperatures less than 15.0°C, which are considered below the habitat preference for albacore (Clemens 1961), are shaded. Fish number 4 remained in the vicinity of a band of water cooler than 15.0°C for nearly the total time it was tracked, but did not appear to enter it (Figure 2). Fish number 6 traveled on a southerly course, in a corridor of warm water which was sandwiched between two wedges of cool water on 25 August, but did not enter the cool water on either side except very briefly at the start of tracking (Figure 4). When the fish passed to the south of the cool water, where there was a large area of water warmer than 15.0°C, the fish changed its direction generally to a more southwesterly course.

## Relationship of Albacore Movements to Upwelling Temperature Fronts

A well-developed temperature front occurs at the boundary between cool, biologically rich

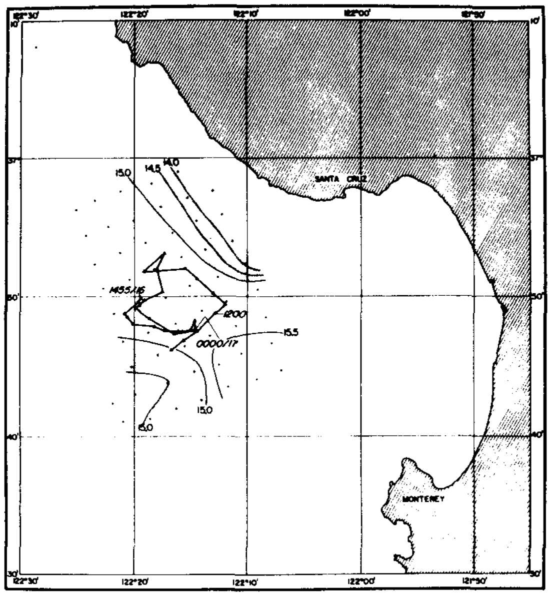


FIGURE 2.—Movements of albacore number 4 as indicated by ultrasonic tracking and contoured field of sea surface temperature in degrees Celsius. Triangles on fish track indicate hourly position. The time and date that tracking commenced is noted at the starting location and shown above and below a slash mark, respectively. The 0000 and 1200 h local time positions are also indicated. Dots show where temperature observations were made by *David Starr Jordan*. Temperatures below 15.0°C are shaded.

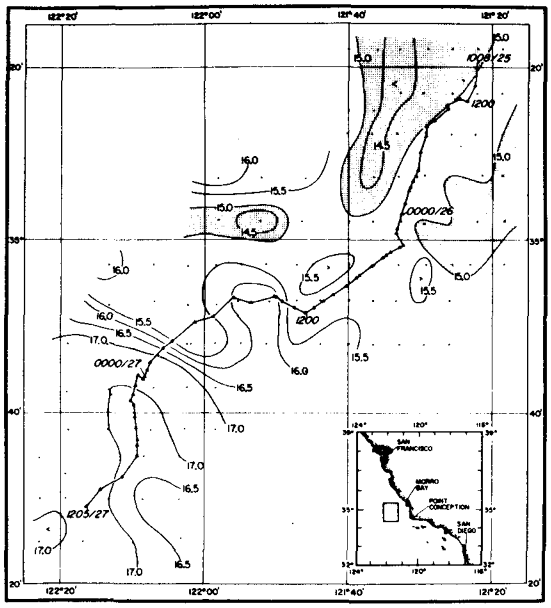


FIGURE 4.—Movements of albacore number 6 as indicated by ultrasonic tracking and contoured field of sea surface temperature in degrees Celsius. Triangles on fish track indicate hourly position. The time and date that tracking commenced is noted at the starting location and shown above and below a slash mark, respectively. The 0000 and 1200 h local time positions are also indicated. Dots show where temperature observations were made by *David Starr Jordan*. Temperatures below 15.0°C are shaded.

upwelled water and warmer, nonupwelled water (Smith 1968). The effects that an upwelling front may have on the movements of albacore were indicated during the ultrasonic tagging experiment. On 17 August, during tracking operations for fish number 4, a relatively well-developed upwelling surface temperature front was observed in the northeast portion of the tracking area. The upwelling was caused by brisk northerly winds which had been blowing for several days. The remainder of the area surveyed has a rather simple surface temperature distribution mostly within the temperature range considered as the habitat preference for albacore (Figure 2).

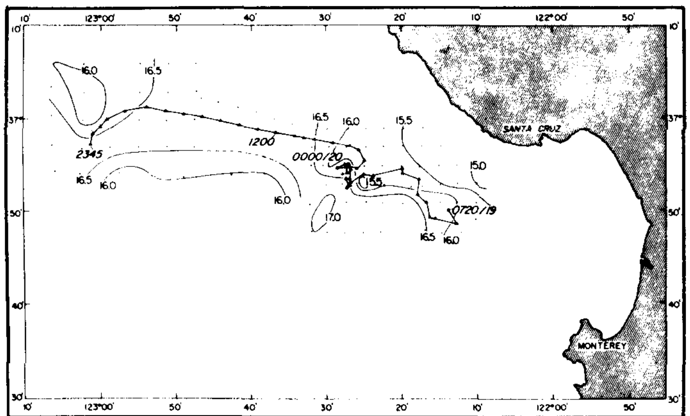


FIGURE 3.—Movements of albacore number 5 as indicated by ultrasonic tracking and contoured field of sea surface temperature in degrees Celsius. Triangles on fish track indicate hourly position. The time and date that tracking commenced is noted at the starting location and shown above and below a slash mark, respectively. The 0000 and 1200 h local time positions are also indicated. Dots show where temperature observations were made by *David Starr Jordan*.

Infrared radiation temperature measurements made during an overflight by the Coast Guard aircraft on 16 August showed that the water on the cold side of the front continued to decrease toward shore to values below 13.0°C.

Fish number 4 traveled in about an 8 × 8 nmi area on the warm side of the upwelling front and in close proximity to it for nearly the total time the fish was tracked. Subsequently, high winds and rough seas made tracking difficult and the signal from the fish was lost during hour 27 of tracking.

Fish number 5 exhibited a much different pattern of movement than did number 4 (compare Figures 2 and 3). It moved many miles from the location where it had been tagged, in a general northwesterly direction, rather than remaining in the local vicinity as fish number 4 had done.

Examination of oceanograhic data revealed that marked changes in the distribution of sea surface temperature had occurred between 17 and 19 August (compare Figures 2 and 3). Upwelling had subsided, the upwelling temperature front was no longer present on 19 August, and the temperature over much of the area had increased by about 1.5°C. The breakdown of the upwelling front and warming was due to a slackening and shifting of the winds to a westerly-southwesterly direction which allowed a thin layer of warmer offshore water to flow toward the coast.

It is presumed that the school of fish with which fish number 4 was traveling remained in the vicinity of the upwelling front to feed in the highly productive water associated with the upwelling. Measurements of chlorophyll were high in the tracking area and showed a very strong positive gradient on the cold side of the upwelling front (Figure 5). Measurements of $^{14}C$ uptake indicated a primary production rate integrated over the euphotic zone (0 to 36 m) of 1,511 mg C/m$^2$ per day. The biomass of potential albacore food organisms was also high, ranging from about 20 to 56 ml/1,000 m$^3$ water strained, in midwater trawl collections made at night in the nearby area where tracking took place (Table 4).

Albacore were frequently seen boiling in the area nearby the upwelling front by personnel aboard *Linda* and *David Starr Jordan*. Also, observers aboard the Coast Guard aircraft noted about 25 to 30 commercial albacore jig boats fishing immediately on the warm side of the front in water warmer than 15.0°C. High biological production in the area of the upwelling front was

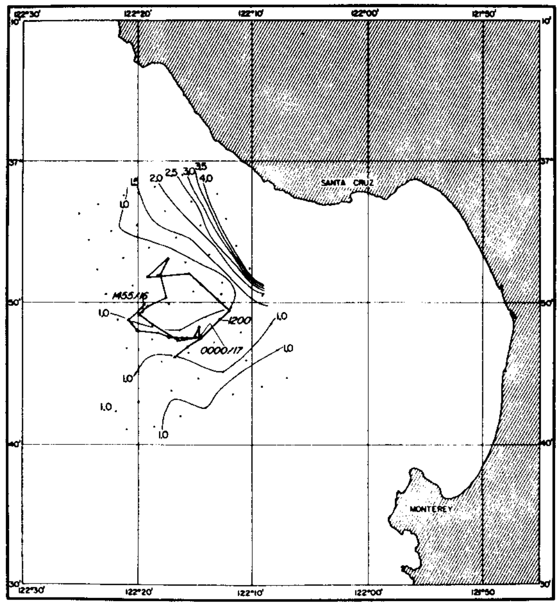


FIGURE 5.—Movements of albacore number 4 as indicated by ultrasonic tracking and the distribution of surface chlorophyll in milligrams per cubic meter.

TABLE 4.—Summary of dates, times, positions, and estimates of potential albacore forage, 1972.

| Fish no. | IKMT no. | Date | Time | Lat. (N) | Long. (W) | Forage biomass (ml/1,000 m$^3$) |
|---|---|---|---|---|---|---|
| 4 | 1 | 15 Aug. | 2200-2240 | 36°50′ | 122°14′ | 28.8 |
| | 2 | 16 Aug. | 2159-2238 | 36°47′ | 122°15′ | 36.2 |
| | 3 | 17 Aug. | 2137-2215 | 36°55′ | 122°24′ | 56.2 |
| | 4 | 18 Aug. | 0032-0111 | 36°53′ | 122°16′ | 51.5 |
| | 5 | 18 Aug. | 0130-0210 | 36°52′ | 122°19′ | 30.4 |
| | 6 | 18 Aug. | 0232-0311 | 36°49′ | 122°22′ | 37.7 |
| | 7 | 18 Aug. | 0352-0430 | 36°50′ | 122°11′ | 30.7 |
| | 8 | 18 Aug. | 0516-0553 | 36°41′ | 122°19′ | 29.8 |
| 5 | 9 | 21 Aug. | 2116-2150 | 37°06′ | 122°50′ | 5.7 |
| | 10 | 21 Aug. | 2236-2314 | 36°57′ | 122°59° | 10.1 |
| | 11 | 22 Aug. | 0032-0115 | 36°54′ | 122°38′ | 24.5 |
| | 12 | 22 Aug. | 0152-0231 | 36°48′ | 122°30′ | 23.1 |
| | 13 | 22 Aug. | 0302-0341 | 36°55′ | 122°25′ | 10.6 |
| | 14 | 22 Aug. | 0412-0450 | 36°52′ | 122°17′ | 24.9 |
| 6 | 15 | 27 Aug. | 2119-2156 | 34°40′ | 122°14′ | 5.8 |
| | 16 | 27 Aug. | 2241-2320 | 34°48° | 122°02′ | 8.0 |
| | 17 | 28 Aug. | 0040-0122 | 34°53′ | 121°51′ | 5.9 |
| | 18 | 28 Aug. | 0214-0251 | 35°07′ | 121°29′ | 10.1 |
| | 19 | 28 Aug. | 0325-0402 | 35°15′ | 121°26′ | 19.6 |

also indicated by large numbers of sea birds and numerous sightings of marine mammals, including blue whales and other whales.

It is possible that fish number 5 and the school it was traveling with left the immediate area where it had been tagged because food organisms were no longer concentrated there due to the breakdown of the upwelling front. This explanation is supported by the observation on 19 August of an overall reduction in the concentration of surface

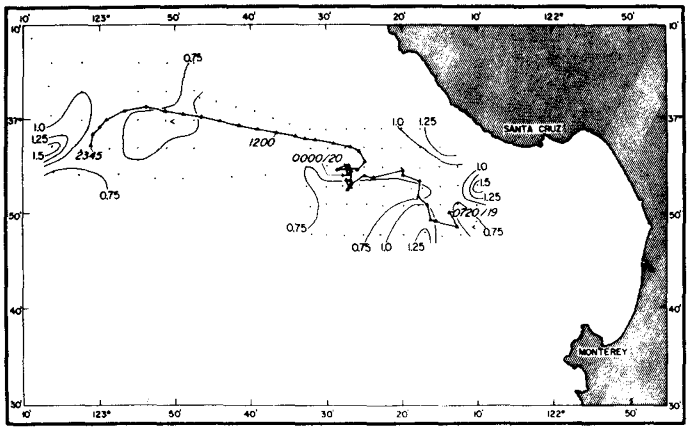


FIGURE 6.—Movements of albacore number 5 as indicated by ultrasonic tracking and the distribution of surface chlorophyll in milligrams per cubic meter.

chlorophyll a, as much as three to four times lower in waters where upwelling had been taking place on 17 August (Figure 6). Also, measurements of $^{14}C$ uptake indicate that the rate of primary production was about 33% lower, 1,014 mg C/m$^2$ per day, than it had been when fish number 4 was tracked. In addition, estimates of biomass of potential albacore forage organisms taken in midwater trawl hauls made during tracking operations for fish number 5 were less, ranging from about 6 to 25 ml/1,000 m$^3$ of water filtered (Table 4), than during tracking operations for fish number 4. (Relatively low chlorophyll a values (Figure 7) and albacore forage biomass values (Table 4) were also observed during tracking operations for fish number 6.)

While tracking information on only two fish does not provide sufficient data from which to make generalizations, the results suggest that 1) albacore concentrate in the vicinity of upwelling fronts, presumably to feed, and 2) albacore move away from the immediate area when upwelling ceases and the upwelling front is no longer present at the surface. Pearcy and Keene (1974) discussed the possibility of albacore congregating in the region of upwelling fronts. The concentration of albacore in the vicinity of upwelling fronts has also been indicated by high catch rates made by fishing and research vessels near upwelling fronts (Pearcy and Mueller 1970; Panshin 1971; Laurs 1973).

## Relationship of Albacore Movements to Other Sea Surface Temperature Fronts

During the tracking operations, it appeared that fish numbers 5 and 6 tended to slow down

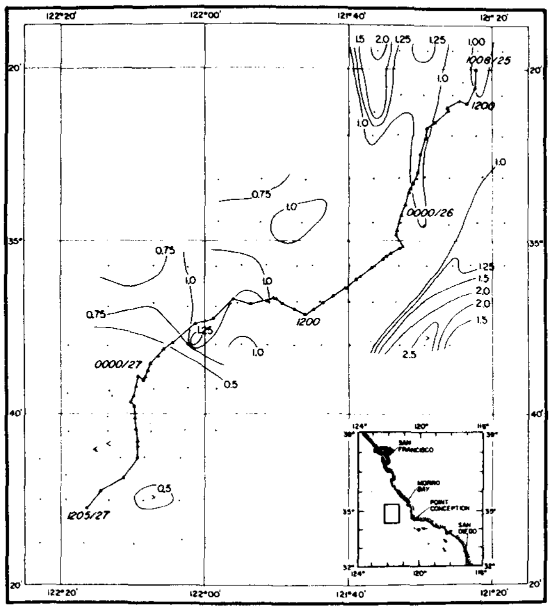


FIGURE 7.—Movements of albacore number 6 as indicated by ultrasonic tracking and the distribution of surface chlorophyll in milligrams per cubic meter.

when crossing temperature fronts where the temperatures on both sides of the front were within the favorable range for albacore. To examine this more closely, mean speeds were estimated for tagged fish when they were within a 5-nmi distance before crossing and after crossing the temperature front and when crossing the front. A sea surface temperature front was defined as a change in surface temperature of 0.5°C or larger in a nautical mile (0.003°C/m). The results are summarized in Table 5 and show that for the three cases examined, 1) the mean speed was slower when crossing the front than it was before

TABLE 5.—Mean speed crossing temperature front[1] and mean speed within 5-nmi radius before and after.

| Item | Fish no. | Date | Time | Total (h) | Total distance (nmi) | (km) | Mean speed (knots) | (cm/s) |
|---|---|---|---|---|---|---|---|---|
| Before | 5 | 8/19 | 1330-1600 | 2.5 | 5.0 | 9.3 | 2.0 | 103 |
| At front | 5 | 8/19-20 | 1600-0300 | 11.0 | 7.8 | 14.4 | 0.7 | 36 |
| After | 5 | 8/20 | 0300-0800 | 5.0 | 7.0 | 13.0 | 1.4 | 72 |
| Before | 6 | 8/26 | 1700-1900 | 2.0 | 5.6 | 10.4 | 2.8 | 144 |
| At front | 6 | 8/26 | 1900-2100 | 2.0 | 3.7 | 6.9 | 1.8 | 93 |
| After | 6 | 8/26-27 | 2100-0200 | 5.0 | 8.0 | 14.8 | 1.6 | 83 |
| Before | 6 | 8/26 | 0800-1230 | 4.5 | 6.1 | 11.3 | 1.4 | 72 |
| At front | 6 | 8/26 | 1230-1400 | 1.5 | 2.0 | 3.7 | 0.7 | 36 |
| After | 6 | 8/26 | 1400-1600 | 2.0 | 5.2 | 9.7 | 2.6 | 134 |

[1] $\Delta T \geq 0.5°C/1.0$ nmi.

crossing the front in all three cases, and 2) the mean speed was slower when crossing the front than after crossing the front in two cases. These data should be viewed with caution, however, because in two instances, daytime and nighttime data were used together and some of the differences in speed may be due to variation associated with time of day. The relationship did hold up well in the single case when daytime data only were used.

We think the changes in swimming behavior observed at temperature fronts reflected perception and response to the increased temperature gradient per se. In the case of the alteration in the swimming pattern of fish number 5 as it encountered a temperature front at lat. 36°53′N, long. 122°27′W (Figure 3), there was no sharp gradient in any of the other environmental parameters we measured.

That tunas can perceive abrupt temperature changes as small as 0.1°C has been demonstrated by Steffel et al. (1976) for captive kawakawa, *Euthynnus affinis*. Moreover, a mechanism has recently been suggested (Neill et al. in press) whereby tunas might be able to orient themselves in temperature gradients much gentler than those of our fronts, perhaps even as slight as 0.0001°C/m; this speculative mechanism invokes the large thermal inertia of tunas as a device for thermal "memory."

### Movements of Albacore in Relation to Vertical Thermal Structure

The availability of albacore in offshore waters has been shown to be related to vertical thermal structure (Laurs and Lynn[7]). However, no obvious relationship was observed in this study between the movements of sonic-tagged albacore in coastal waters and subsurface temperature structure. This may be due to the complicated vertical temperature structure that was observed in the areas where fish were tracked and the lack of data on the depth of the fish.

## SUMMARY

Six albacore were tagged and tracked with ultrasonic equipment for periods ranging from 2 to 50 h and distances ranging from 6.5 to 150.7 km (3.5 to 81.3 nmi). The average swimming speed for these fish tracked between 27.8 and 50.0 h was 1.6 knots (82 cm/s) with each fish exhibiting slightly faster swimming speeds during the day than during the night. The mean swimming speeds observed during the tracking experiment are similar to estimates of swimming speed derived from passive tagging results and about twice the calculated minimum swimming speed necessary to maintain hydrostatic equilibrium.

The tracking experiment indicated that oceanographic conditions may play an important role in the local concentrations and movements of albacore in coastal waters. The movements of fish appeared to be related to the distribution of sea surface temperature, with transmitter-tagged fish spending very little time in water with surface temperatures less than 15.0°C. The results also indicate that upwelling temperature fronts may markedly influence the local concentration of albacore, with albacore tending to concentrate in the vicinity of upwelling fronts, presumably to feed, and moving away from the immediate area when upwelling ceases and the upwelling front is no longer present at the surface. There was also some indication that albacore tended to slow down when crossing sea surface temperature fronts

[7]Laurs, R. M., and R. J. Lynn. 1974. The offshore distribution and availability of albacore during early-season and the migration routes followed by albacore into North American waters. SWFC Admin. Rep. LJ-74-47:19-46.

where the temperatures on both sides of the front were within the optimal range for albacore.

Finally, the tracking experiment demonstrated that acoustic tracking of albacore is feasible and that it can be a useful tool in studies designed to understand better the relationships between albacore and the marine environment.

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