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No. 25

PURSE-SEINER CATCH RATES OF YELLOWFIN TUNA >7.5 KG, WITH AND WITHOUT DOLPHINS, IN THE EASTERN PACIFIC OCEAN

by

R. G. Punsly and P. C. Fiedler

La Jolla, California

1996

PREFACE

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by

R. G. Punsly and P. C. Fiedler [1]

Abstract

Yellowfin tunas are caught by purse seiners in the eastern Pacific Ocean in primarily free-swimming schools, schools associated with floating objects and those associated with dolphins. Medium and large yellowfin (>7.5 kg) are more desirable than small ones because they normally bring a greater price per unit of weight. Yellowfin caught with dolphins tend to be larger and closer to the optimum size for yield per recruit than those caught in other types of schools. Thus, targeting dolphin-associated yellowfin has usually resulted in greater yields. Recent efforts to reduce or eliminate incidental dolphin mortality brings up the obvious question: Under what conditions can yellowfin >7.5kg, not associated with dolphins, be caught at the same rate as dolphin-associated yellowfin? We analyzed the relationships between 7.5kg+ yellowfin catch rates, during 1980-1990, and various environmental and spatiotemporal factors, using general linear models. Season and area explained far more variation in catch rates than any combination of environmental variables. For example, good catch rates (750 kg per hour searched) of yellowfin >7.5kg from non-dolphin sets were common in the southeastern tropical Pacific during January-October, although dolphin-set catch rates were still higher (about 1.0 mt per hour), and only 6% of the non-dolphin-set catch came from this season-area. The greatest non-dolphin-set catch rates occurred in cooler waters (23°C) than did the greatest dolphin-set catch rates (26°C). One unexpected result was that the effects of the environment on catch rates were not constant over time. For example, during the 1982-1983 El Niño many of the environmental factors had different effects on dolphin-set catch rates than they had in most other years. Although the environmental range within which non-dolphin sets occurred was greater than that of dolphin sets, their geographical distribution was more limited during most points in time. High catch rates of yellowfin >7.5kg, not associated with dolphins, have been realized by some seiners, over a wide range of environmental conditions. These occasional high catch rates suggest that it might be possible to improve fishing methods and deployment of effort to increase fishing success for yellowfin >7.5kg not associated with dolphins.

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Introduction

The purse-seiner fishery for tunas in the eastern Pacific Ocean is one of the world's most productive. Recently, the annual yields have been about 400,000 mt of tuna, mostly yellowfin (*Thunnus albacares*, Bonnaterre, 1788) and skipjack (*Katsuwonus pelamis*, L.). The eastern Pacific produces some of the greatest yellowfin purse-seiner catches in the world, about 300,000 mt per year since 1986. These large catches may in part be attributable to the uniquely strong association between yellowfin and certain species of dolphins in the eastern Pacific: primarily spotted dolphin (*Stenella attenuata*, Gray, 1846), but also spinner (*S. longirostris*, Gray, 1828) and common (*Delphinus delphis*, L.) dolphins. On the average, about 60% of the yellowfin catch in the eastern Pacific Ocean comes from dolphin-associated schools (Joseph, 1994). Dolphins are easier to detect than yellowfin because they are larger and closer to the surface. Also, yellowfin associated with dolphins are less likely to escape while the net is being set because the dolphins can be herded back to the net and the tunas will follow. Consequently, their vulnerability to purse-seiners is greater (Punsly *et al.*, 1994). Calkins (1965) found that yellowfin caught with dolphins tend to be larger (~20 kg average) than yellowfin from non-dolphin sets (~5 kg average). A 7.5kg yellowfin is between the modes of dolphin and non-dolphin sets (Figure 1). Catches of larger yellowfin, according to Punsly *et al.* (1994), result in a greater yield per recruit and bring a greater price per unit of weight (National Marine Fisheries Service, 1992). Thus far, locating and capturing yellowfin associated with dolphins has been the most efficient way of capturing fish over 7.5kg.

Fishermen attempt to release the dolphins from the net while pursing, but strong subsurface currents, equipment malfunctions, disoriented dolphins, and other factors make it impossible to save all of the dolphins all of the time. Sometimes dolphins become entangled in the nets and suffocate. Since the 1970s, research by purse-seiner fishermen, the U.S. National Marine Fisheries Service (NMFS), the Inter-American Tropical Tuna Commission (IATTC), and the Programa Nacional para el Aprovechamiento del Atún y la Protección del Delfín in Mexico resulted in modifications of gear and techniques which substantially reduced incidental dolphin mortality. However, because the use of dolphins is not consistent with either the intent of the U.S. Marine Mammal Protection Act (NRC, 1992) or some people's sentiments for dolphins, improved methods for catching yellowfin >7.5kg, without setting on dolphins, are being investigated.

Purse-seiner catch rates have been related to environmental factors, such as thermocline depth (Green, 1967; Peterson, 1982, p 73-75). In this study we examined several environmental and spatiotemporal factors, hoping to find conditions under which purse seining has been good for yellowfin >7.5kg not associated with dolphins. Climatological (1960-1991) fields of surface temperature, wind stress, thermocline depth, and thermocline strength are shown in Figure 2. These fields are means of monthly climatologies spatiotemporally stratified from the same databases used for the monthly fields. The area in which the eastern Pacific purse-seine fishery operates is characterized by a strong, shallow thermocline and, in the heavily fished region between the equator and 20°N, warm surface water and converging trade winds. The cold-water tongue along the equator is the result of equatorial upwelling. The topography of the thermocline consists of two zonal ridges, along 10°N and the equator, and a general east-west slope from close to 40 m near the coast to 120 m at the offshore limits of the fishery. These patterns vary somewhat both seasonally and interannually (Fiedler, 1990).

Materials and analytical methods

Environmental data

We used bathythermograph and wind data to derive estimates of environmental variables (Table 1). The bathythermograph data were acquired from a variety of sources, including fishing, commercial, military and research vessels (Table 2). Mixed-layer depth (MLD), which corresponds approximately to the top of the thermocline, was defined as the depth at which temperature is 0.5°C less than surface temperature. In the tropical Pacific, the 20°C isotherm is typically near the middle of the thermocline, and has been used as an index of thermocline depth (Kessler, 1990). The 14°C isotherm is near the bottom of the thermocline (Meyers, 1979). In this study, thermocline depth was defined as the depth of the maximum temperature gradient over 10-meter intervals and thermocline strength as the magnitude of that gradient.

Temperature data for 1980 through 1990, from 20°S to 30°N latitude and from the coast to 150°W longitude were stratified into 2°x2° quadrangle months by the method described in the Appendix. Monthly coverage was low in some areas (Figure 3).

Logbook data

The principal source of data for catch, effort, and vessel characteristics is the IATTC logbook database, described by Orange and Calkins (1981), Punsly (1983), and Allen and Punsly (1984). This database has information on the daily fishing activities of about 90% of the purse seiners fishing for yellowfin in the eastern Pacific. Data for 20,000 to 50,000 sets are collected annually. The data used in this study include estimates of the amounts of each species caught, location, starting and ending times, school type (free swimming, dolphin-associated, or floating-object-associated, Greenblatt, 1979), and vessel characteristics (holding capacity, speed, net dimensions and the presence or absence of helicopters and bird radar).

Catch

The catch of yellowfin >7.5kg in each set was calculated by first estimating the number of fish in each semi-annual age group (see the discussion of the X and Y cohorts in Bayliff, 1993, p 66-69), using the method of Punsly and Deriso (1991), and then summing the average weights of fish from semi-annual age groups with monthly average weights greater than 7.5 kg (which corresponds to an average length of 73 cm and an average age of approximately 18.5 months).

Catch rates

Catch rate of yellowfin >7.5kg was defined as the weight (mt) of yellowfin >7.5kg caught per hour of searching. The two basic theoretical components of catch rate are catchability and abundance: $CR = q\bar{N}$, where q is the catchability coefficient and $\bar{N}$ is the average abundance. We did not separate catchability from abundance because we are interested only in their product as a measure of success.

The two basic practical components of purse-seiner catch rates are the catch per set and the searching time between sets. The two components were analyzed separately to get a more precise understanding of how the environment influences catch rates. Two measures of each component were examined. The first measures the catch rates of yellowfin >7.5kg by vessels targeting all sizes of fish, and the second measures catch rates by vessels targeting mostly yellowfin >7.5kg.

The first measure describes the 1980-1990 fishery, which targeted all sizes of fish. Searching time, ST1, was defined as the number of hours searched between sets which yielded more than 2.7 mt (3 short tons) of yellowfin of all sizes. Sets containing less than 2.7 mt are seldom made intentionally. We omitted them from the yellowfin catch rate analyses because they usually indicate unusual circumstances, such as some problems while making the set which result in most of the fish being lost (Allen and Punsly, 1984). Time spent in sets with less than 2.7 mt of yellowfin was not counted as searching time. Data from aborted searches, usually resulting from breakdowns, bad weather, or a decision to run to another area, were not included in the analyses, because the times of these events were not available. Catch per set, CPS1, was defined as the weight of yellowfin >7.5kg landed in the set. CPS1 was zero if at least 2.7 mt small yellowfin, but no yellowfin >7.5kg were estimated to be caught.

The second measure describes a fishery which targets yellowfin >7.5kg. Searching time, ST2, was defined as the number of hours searched between sets which yielded more than 450 kg (½ short ton is the resolution of the database) of yellowfin >7.5kg. Time spent in sets which produced less than 450 kg of yellowfin >7.5kg was not counted as searching time. Also, data from aborted searches were not included in the analyses. The second measure of catch per set, CPS2, is defined as the catch of yellowfin >7.5 kg from sets which produced at least 450 kg of them. Therefore, CPS2 cannot be less than 450 kg. We chose to focus on CPS1 and ST2. CPS1 was preferred over CPS2 because zero catch-per-set of yellowfin >7.5kg data are useful for determining which are the wrong conditions for catching yellowfin >7.5kg. ST2 was preferred over ST1 because ST2 is a better measure of the time needed to locate yellowfin >7.5kg. Overall catch rate of yellowfin >7.5kg was defined as CPS2/ST2, which is a measure of the success of vessels targeting yellowfin >7.5kg.

Catch rate data (ln(CPS1 + 0.1) and ln(ST2)) from 1980-1990 were stratified into 2°x2° quadrangle-months with locally-weighted least-squares regressions (Cleveland and Devlin, 1988) to estimate the values at the midpoints of each quadrangle-month. The logarithmic transformations were applied for two reasons: the data were distributed lognormally (Punsly, 1987) and a multiplicative model is preferable for standardization (Allen and Punsly, 1984). Details on the spatiotemporal-stratification methods are described in the Appendix.

Vessel characteristics

Environmental effects needed to be standardized by vessel effects because vessel characteristics which affect fishing success could be confounded with environmental effects. For example, inshore oceanographic conditions differ from those offshore, and small vessels tend to fish closer to shore. Therefore, vessel characteristics data (Table 1) were also stratified into 2°x2° quadrangle-months for inclusion in the analyses described in the Appendix.

Spatiotemporal factors

Environmental factors were also standardized by years for the following reasons. Both environmental factors and the abundance of yellowfin have annual trends in the eastern Pacific (Figure 4). Although the environmental trends may have contributed to the abundance trend by affecting spawning, recruitment, or mortality, this topic is not within the scope of our study. Therefore, years are used as an independent variable in the regressions to prevent the confounding of local environmental effects with the overall annual abundance trend in the eastern Pacific.

Punsly (1987) categorized yellowfin catch rates into 20 season-areas (Figure 5). Knowing which season-areas tend to have good catch rates of yellowfin >7.5kg is as useful, although less informative, than knowing which environmental conditions produce good catch rates. Therefore, we analyzed the effects of season-area on searching time and catch per set.

General linear model analyses

General linear models (GLMs) are commonly used to explain the effects of multiple factors on catch rates (Gavaris, 1980; Allen and Punsly, 1984). The dependent variable in a GLM should be approximately normally distributed in order for significance tests to be valid. However, the regression coefficients will be unbiased even if the data are not normal (Searle, 1971). Figure 6 shows that ln(CPS1 + 0.1) and ln(ST2) are approximately normal. Independent variables in GLMs must be either linearly correlated with the dependent variable (linear covariates), or be categorical data which get converted to dummy variables in the regression within the GLM (classifications; *e.g*, season-area). Non-linear covariates can be transformed into linear covariates or broken down into classifications. Visual examinations of box plots (McGill, *et al.*, 1978) were used to determine whether the relationships between covariates and dependent variables were linear (see example in Figure 7). If a relationship was not linear, the box plots were useful for deciding what transformation or categorization was necessary.

Results

Mean 1980-1990 geographical distributions of catch per set and searching time are shown in Figure 8. The greatest catch rates of yellowfin >7.5kg per dolphin set occurred mostly along the southern and western edges of the purse-seine-fishery area, while the greatest yellowfin >7.5kg catches per non-dolphin set occurred on its southern and eastern edges. Both catches per set and searching times indicated poor fishing for yellowfin >7.5kg for all set types off Baja California. Searching times were also very long for non-dolphin sets near the equator and for dolphin sets near the equator east of 100°W.

All of the significant environmental, spatiotemporal, and vessel factors combined explained about 35% of the variation in catch per set, and about 20% of the variation in searching time between schools of yellowfin >7.5kg (Table 3). Season-area was the best descriptor of catch per set. Year was the best descriptor of searching time. Environmental factors explained only 1% to 3% of the variation in catch rate, regardless of whether other spatiotemporal factors were included. Vessel efficiency factors accounted for about 1% to 5% of the variances.

Interactions

All of the possible two-way interactions were examined. None were significant except those involving years or season-areas. Significant interactions with years indicate that the environmental effects were inconsistent over years. During the 1982-1983 El Niño, most of the environmental factors examined had almost the opposite effect that they had in non-El Niño years. For example, searching times in 1983 were negatively correlated with mixed-layer depth and 14°C isotherm depth for non-dolphin and dolphin sets (Figure 9), respectively, while these correlations were positive overall.

Although most of the interactions between environmental factors and season-areas were significant, we excluded them from the analyses because we were unable to relate the regression coefficients for the environmental factors within season-areas, some of which had extreme nonsensical values, to any known or imaginable oceanographic or biological phenomena. This was probably a consequence of the small range of the environmental variables within most season-areas, which made the regression coefficients meaningless when extrapolated outside of the range.

Season-areas

CPS1 was greater for dolphin sets than non-dolphin sets in all season-areas (Table 4). This result is not surprising because vessels making non-dolphin sets frequently target small yellowfin and skipjack. However, CPS2, which is a measure of catch per set when targeting yellowfin >7.5kg, was slightly greater for non-dolphin sets than for dolphin sets in the northeastern tropical Pacific during July-August and November-April, and off Baja California during April-June. In addition, non-dolphin catch per set, CPS2, (Table 4) was greater than 80% of dolphin-set CPS2 in the northeastern tropical Pacific during rest of the year, the southeastern tropical Pacific year round, the offshore northeast tropical Pacific during October-March, and off Baja California during November-March. Dolphin sets were rare in the Peru current, especially between March and October.

Searching times between schools of yellowfin >7.5kg, ST2, were longer for non-dolphin sets than for dolphin sets in most season-areas (Table 4). However, searching times were actually shorter between non-dolphin sets than between dolphin sets in the southeastern tropical Pacific during March-October, in the Gulf of Panama during May-August, and in the Peru Current during the only season in which dolphin sets were made, November-February. Non-dolphin searches were only 15% longer than dolphin searches off Baja California during November-March, and the Gulf of Panama during February-April.

Catch rates, CPS2/ST2, were greater for dolphin sets than non-dolphin sets in all season-areas except those in the Peru Current where dolphins sets are rare (Table 4). However, a statistical comparison is possible in this region only during November-February when non-dolphin fishing for yellowfin >7.5kg yielded 40% greater catch rates than dolphin-set fishing. Non-dolphin set catch rates were at least 90% of dolphin set catch rates in the southeast tropical Pacific during March-October, the Gulf of Panama during May-August and off Baja California during November-March. These season areas combined account for about 8% of the total catch of yellowfin >7.5kg and about 25% of the non-dolphin-set catch. The best purse-seine fishing for yellowfin >7.5kg not associated with dolphins appears to be in the southeastern tropical Pacific during January-October. However, this season-area only produced about 6% of the catch of yellowfin >7.5kg.

The environment

Environmental data were included in the GLMs, both with and without season-area. The regression coefficients for all of the significant environmental factors did not change significantly depending on whether season-area was included in the models. Therefore, season-area effects must be caused by other factors affecting catchability, such as significant environmental factors we did not analyze or seasonal patterns in behavior (*e.g.*, vertical movement, horizontal movement, or schooling).

The effects of the environment on CPS1 and ST2 are shown in Tables 5 and 6. The regression coefficients in Table 5 show the additive effects per standard deviation of the environmental factors on ln(CPS1 + 0.1) and ln(ST2). The coefficients in Table 6 were backtransformed to show the multiplicative effects of the environmental factors on CPS1 and ST2 in original units (*e.g.*, °C or m).

More environmental factors had significant effects on catch per dolphin set than on catch per non-dolphin set (Table 7). However, this may be an artifact due to the larger sample size for dolphin sets (6117 versus 2538 quadrangle-months). Sea-surface temperature had a negative quadratic effect on both the catch per dolphin and non-dolphin set. Maximum catches per set of yellowfin >7.5kg occurred at 26°C for dolphin sets and 23°C for non-dolphin sets. Thermocline temperature, thermocline strength, and wind stress appeared to affect only catch per dolphin set. Catch per dolphin set decreased about 10% for each 1°C increase in thermocline temperature and increased about 0.1% per m^2s^{-2} of pseudostress. Thermocline strength had a quadratic effect on catch per dolphin set, with the minimum at 0.25°C m^{-1}.

Searching times between non-dolphin sets increased 1% per meter of mixed layer depth; whereas, searching times between dolphin sets increased about 0.5 % per meter of the 14°C isotherm depth (Table 6). Thermocline temperature had a quadratic effect on non-dolphin set searching times, with the minimum searching time occurring when the thermocline temperature was 19°C. Like the 23°C optimum SST for non-dolphin catch per set, this is relatively cold for the fishery area.

The greatest environmental effect on the fishery was the cessation of effort in high winds (> 8 or 9 m s^{-1}). Effort south of the equator was reduced during southern winter, when the intertropical convergence zone (ITCZ) has shifted north and the southeast trade winds are strong. Effort north of the equator and west of 120°W usually ceased during northern winter when the ITCZ has moved south and the northeast trade winds are strong. Because no catch data were available, quadrangle-months with high winds could not be part of the catch rate analyses.

Discussion

The results of this study clearly indicate that yellowfin >7.5kg were most often caught by seiners in the eastern Pacific when they were associated with dolphins. In the southeastern tropical Pacific, non-dolphin set catch rates of yellowfin >7.5kg were almost as great as the overall eastern Pacific average dolphin-set catch rate. But even in this region, catch rates in dolphin sets were greater than in non-dolphin sets. Length-frequency distributions of purse-seiner caught yellowfin suggest why catch rates on dolphin sets are better: there are minima in the non-dolphin-set catch of yellowfin between 70 and 100 cm in all oceans. Punsly *et al.* (1994) showed that catchability of this size of yellowfin was very low for non-dolphin sets in the eastern Pacific. Studies showing 70-100 cm minima in the length frequencies of seiner-caught yellowfin in other oceans include Fonteneau *et al.* (1988) for the Atlantic, Coan (1994) for the western Pacific and Marsac (1992) for the Indian Ocean. Apparently, the large catches made by the eastern Pacific yellowfin purse-seine fishery are due to the strong association of 70-100 cm yellowfin with dolphins, which results in greater catchability and yield per recruit than non-dolphin set fishing, which concentrates mostly on small fish.

The environmental range of non-dolphin sets appeared to be greater than dolphin sets (*e.g.* Figure 10). Most of the dolphin-set catches occurred under the following conditions: SST between 25 and 29°C, TD between 50 and 90m, TAU less than 80 m^2s^{-2}, and TS less than .2 or greater than .3°C m^{-1}. Outside this environmental range, most yellowfin were caught in non-dolphin sets. For example, non-dolphin-set catches were common in SSTs between 20°C and 29°C (Figure 10). On the other hand, during most months of most years, the geographical range of non-dolphin sets has been smaller than that of dolphin sets. Perhaps, during some years, the geographical range of non-dolphin sets could be expanded because the environmental range of non-dolphin-set catches is greater than that of dolphin sets. However, generalizations such as these could be misleading because the environment impacts catch rates differently, depending on season, area and year.

The state of the tropical Pacific Ocean was anomalous from mid-1982 through late 1983, when the strongest El Niño event of the century occurred (Enfield, 1989). During this event, SSTs and isotherm depths were at their greatest levels, while catch rates of yellowfin >7.5kg from dolphin sets were at the lowest level (Figure 11). Although the abundance of yellowfin was low during 1983, we still expected environmental covariates to explain some of the decline in the catch rate. However, during the 1982-83 El Niño, the relationships between the dolphin-set catch rates and the environment were different than for all years combined. For example, catch per dolphin set decreased linearly with thermocline strength while this relationship was parabolic for all years combined. Searching time between non-dolphin sets decreased as the depth of the mixed layer increased; whereas this correlation was positive during most years. In 1983, searching times between dolphin sets decreased as the depth of the 14°C isotherm increased (at least up to 150 m), while they increased in most years (Figure 9). Dolphin-set catch rates over deep (140m-150m) 14°C isotherms was approximately the same as in other years. The negative effect of the 1982-83 El Niño on catch rates increased as isotherm depths decreased. Since isotherm depths tend to decrease toward the center of the fishery, the catch rates were most negatively affected there. The reversal of the effects of the environment during the 1982-83 El Niño lead us to conclude that the effect of the environment on catch rates is indirect. In other words, the environment affected something intermediate, perhaps the abundance or distribution of prey species which tunas and dolphins hunt together, which resulted in poor fishing.

Temporal variability in the tuna-dolphin bond may be a key to increasing non-dolphin catch rates. Punsly (1987) showed that yellowfin catch rates recovered from the 1982-83 El Niño first for sets on free-swimming schools in 1983, then on dolphin-associated schools in 1984. Perhaps the environmental conditions during 1982-83 El Niño somehow broke or weakened the tuna-dolphin bond which resulted in yellowfin being more available without dolphins than with them. Suppose that on the southern edge of the fishery, where the best catches of yellowfin >7.5kg in non-dolphin sets have historically occurred, small-scale environmental factors change more rapidly over time and space, resulting in repeated breaking and remaking of the tuna-dolphin bond. Good opportunities for catching yellowfin >7.5kg in non-dolphin sets might occur just before or just after the environment becomes productive for dolphin sets. Under less extreme conditions, the tuna-dolphin bond may not break, or fishermen may have less time to find free-swimming, yellowfin before they re-associate. However, we cannot test any of these hypotheses because the quantity of fine-resolution data collected to date has not been sufficient for analysis.

The strong, shallow thermocline in the eastern tropical Pacific probably influences the foraging behavior of tunas and dolphins: vertically migrating prey are concentrated just above it at night (Fiedler and Barlow, *in prep.*), and it strongly influences the vertical movement of yellowfin (Carey and Olson, 1982; Holland *et al.*, 1990) and dolphins (Bayliff, 1993: p 60-63). The eastern tropical Atlantic also has a strong, shallow thermocline along the equator (Houghton, 1983). However, the strong seasonal variability of the thermocline in the Atlantic is comparable to the interannual variability associated with El Niño in the Pacific (Philander, 1990). Thus, the thermocline in the eastern equatorial Atlantic is shoaled only during June-September, when the southeast trade winds are strong (Houghton, 1983). Perhaps such variability has hindered the evolution of a strong tuna-dolphin bond.

Our study has not addressed effects of environmental variability on scales smaller than one month or shorter than 200 km, which are needed to analyze the effects of thermal fronts, eddies, equatorial long waves, hurricanes, and squalls. These scales cannot be resolved with the data currently available. Small-scale environmental variability almost certainly affects the availability and abundance of tunas. For example, albacore tuna (*Thunnus alalunga*, Bonnaterre, 1788) tend to be caught on the seaward side of coastal fronts off California, presumably where the water is clear enough for albacore to see prey aggregations (Laurs *et al.*, 1984). Murphy and Shomura (1972) argued that surface schooling tunas in the central Pacific were more abundant near fronts north of the equator, where their prey concentrate. Prey availability and foraging behavior are also likely to be important factors influencing the catch rates of all sizes of yellowfin from all set types in the eastern Pacific. Although the abundance and distribution of yellowfin prey cannot be readily monitored throughout the almost 15 million square kilometers of yellowfin habitat in this region, direct or indirect measures of this or other environmental factors might be obtainable. For example, water transparency and phytoplankton biomass can be estimated from data collected by ships of opportunity or satellite ocean color sensors. Estimates of other factors, such as surface currents and associated convergences and divergences, or even thermal structure and circulation, may, in the future, become available from high-resolution general circulation models assimilating observed forcing variables (Rhodes *et. al*, 1994). It should also be noted that the r^2 values in Table 3 are partly determined by the spatiotemporal resolution used in this study. For example, Punsly (1987), using individual sets as observations, could only explain 10% of the variance using a model with 147 degrees of freedom. Our data were smoothed into 2°x2° quadrangle-months, removing some of the noise. However, yellowfin are very mobile in 3 dimensions, and both the monthly abundance and vulnerability to purse seiners are highly variable within each 2°x2° quadrangle, regardless of the environmental conditions.

In the past, some very high catch rates of yellowfin >7.5kg not associated with dolphins have been realized over a wide range of environmental conditions. Closer examination of the data reveals that these unusually high catch rates were achieved by only a few vessels. This suggests that, perhaps, other vessels might be able to modify both their deployment of effort and fishing methods to increase their catches of yellowfin >7.5kg not associated with dolphins. Catch rates of yellowfin >7.5kg from non-dolphin sets will continue to be lower than those for dolphin sets unless fishermen can improve their skills or methods in non-dolphin sets.

The environmental variables we analyzed combined with the fairly coarse resolution of the data, can only give initial indications of how to better locate and capture yellowfin >7.5kg not associated with dolphins. Future research on 1) small-scale environmental changes, such as fronts and storms, 2) other environmental covariates such as currents, salinity, water color, equatorial long waves, and 3) the distribution of floating objects, zones of convergence, and biological factors, such as local production and the distribution and abundance of prey, competitors, and other associated species, including birds, may lead to a better understanding of yellowfin behavior. We may then be able to more efficiently predict how to locate and capture schools of yellowfin >7.5kg not associated with dolphins. Our results, while quite general, provide a preliminary basis for determining the seasons, areas, and environmental conditions in which both future research and experimental fishing might be most successful.

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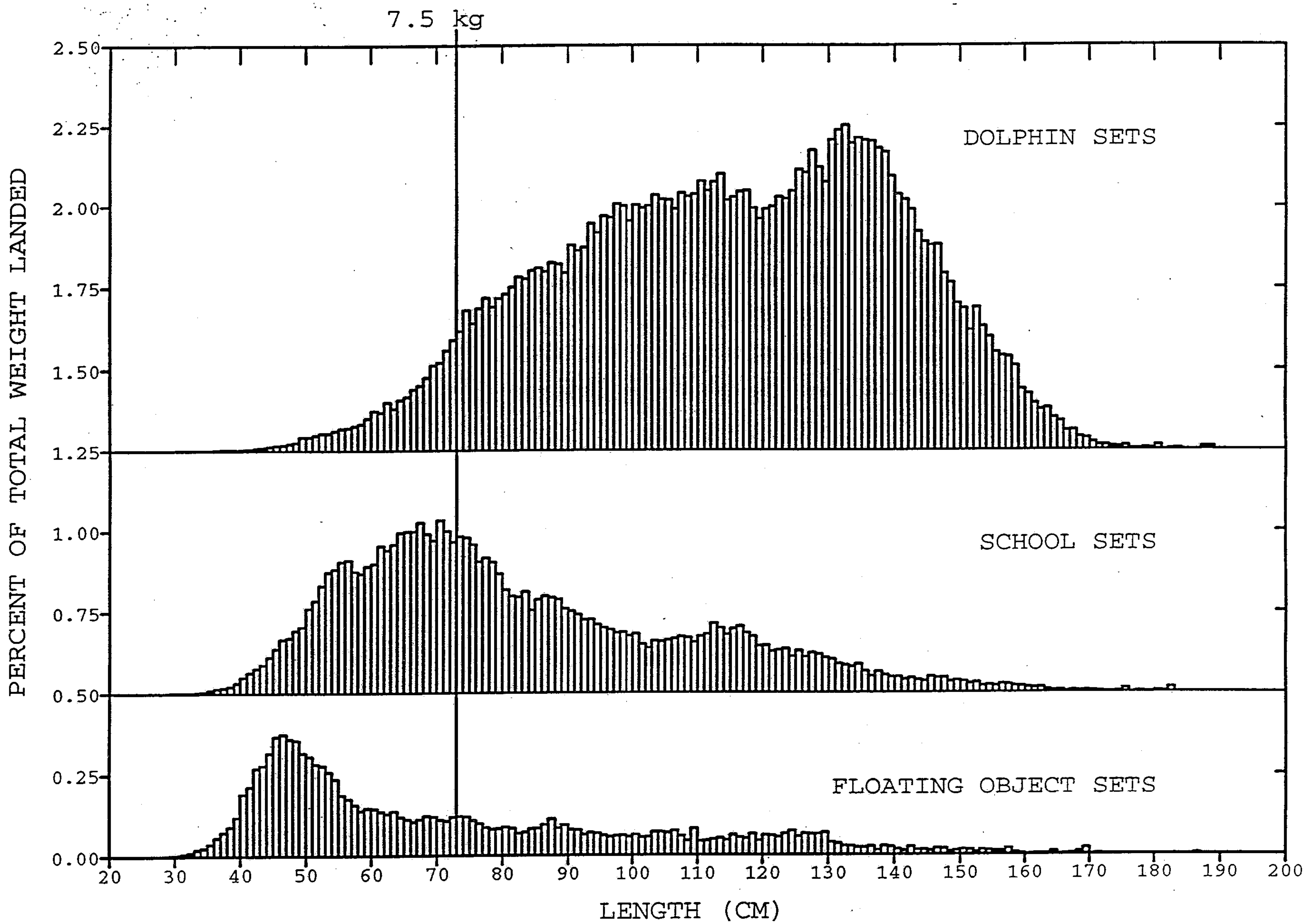

Figure 1. Estimated percent of weight of yellowfin tuna caught by purse seiners in the eastern Pacific Ocean, during 1980-1990, provided by Patrick K. Tomlinson, IATTC. During this time period, dolphin, school, and floating object sets provided 62.8%, 25.4%, and 11.8% of the yellowfin catch, respectively.

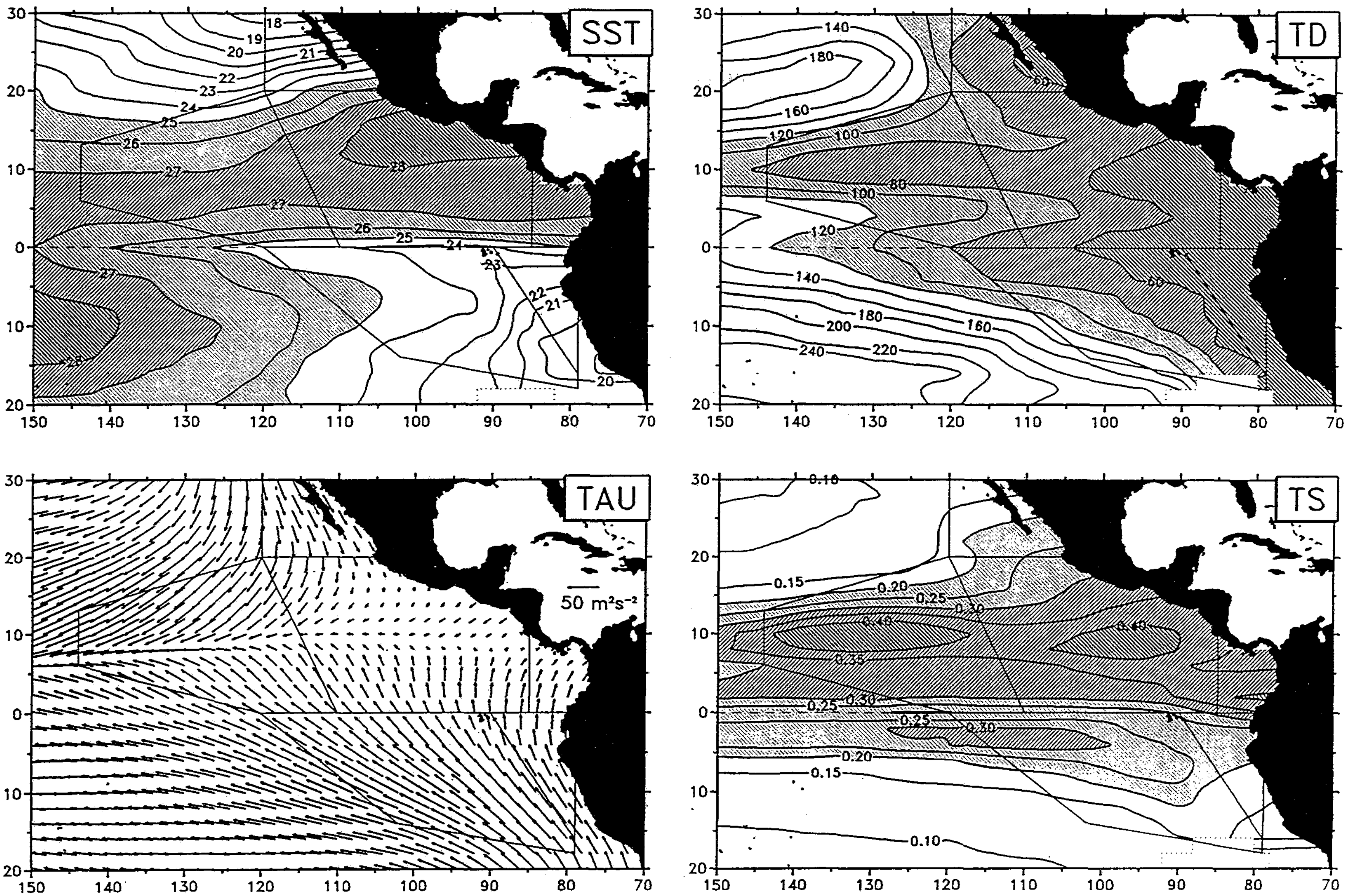

Figure 2. Climatological (1960-1991) fields of mean sea surface temperature (SST, °C), thermocline depth (TD, m), wind pseudostress (TAU, m^{2}s^{-2}), and thermocline strength (T~~D~~ S, °C m^{-1}). Thin lines mark purse-seine fishery areas used in the season-area classification.

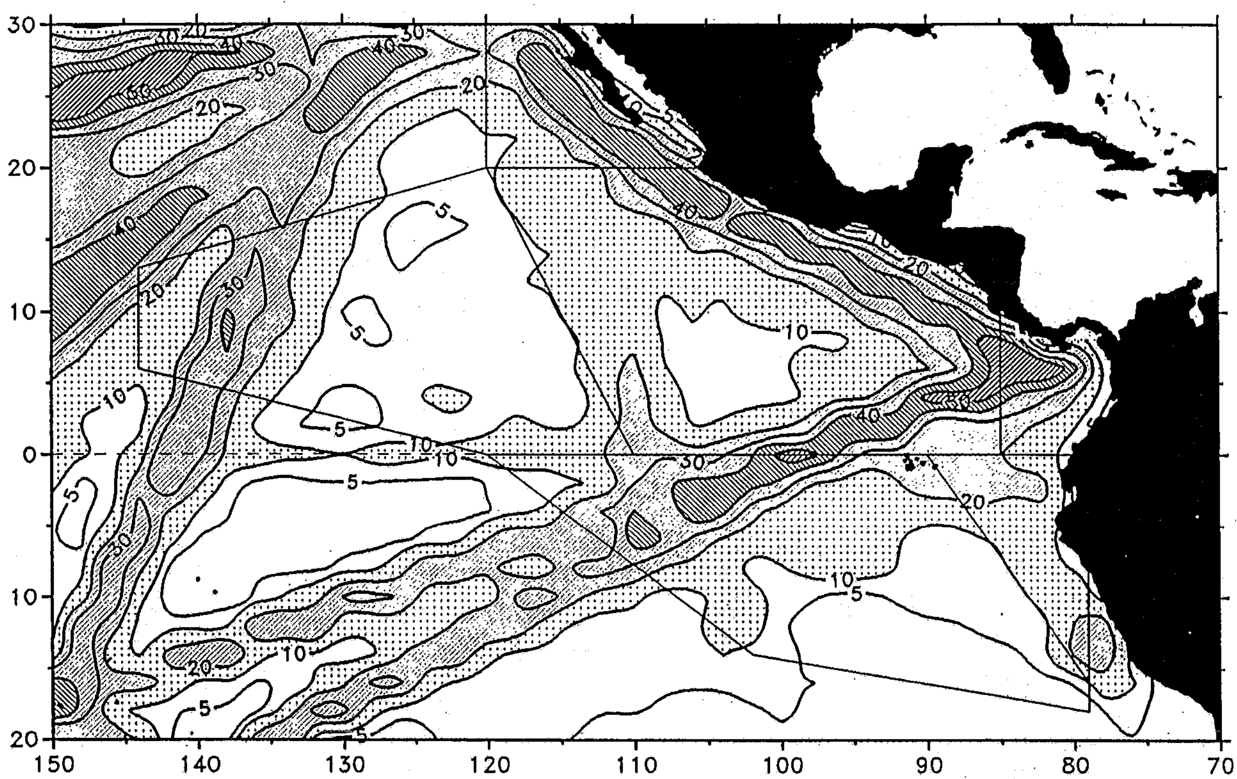

Figure 3. Percent monthly coverage of bathythermograph data in monthly 2°x2° quadrangles, 1980-1990. Thin lines mark purse-seiner fishing areas used in the season-area classification.

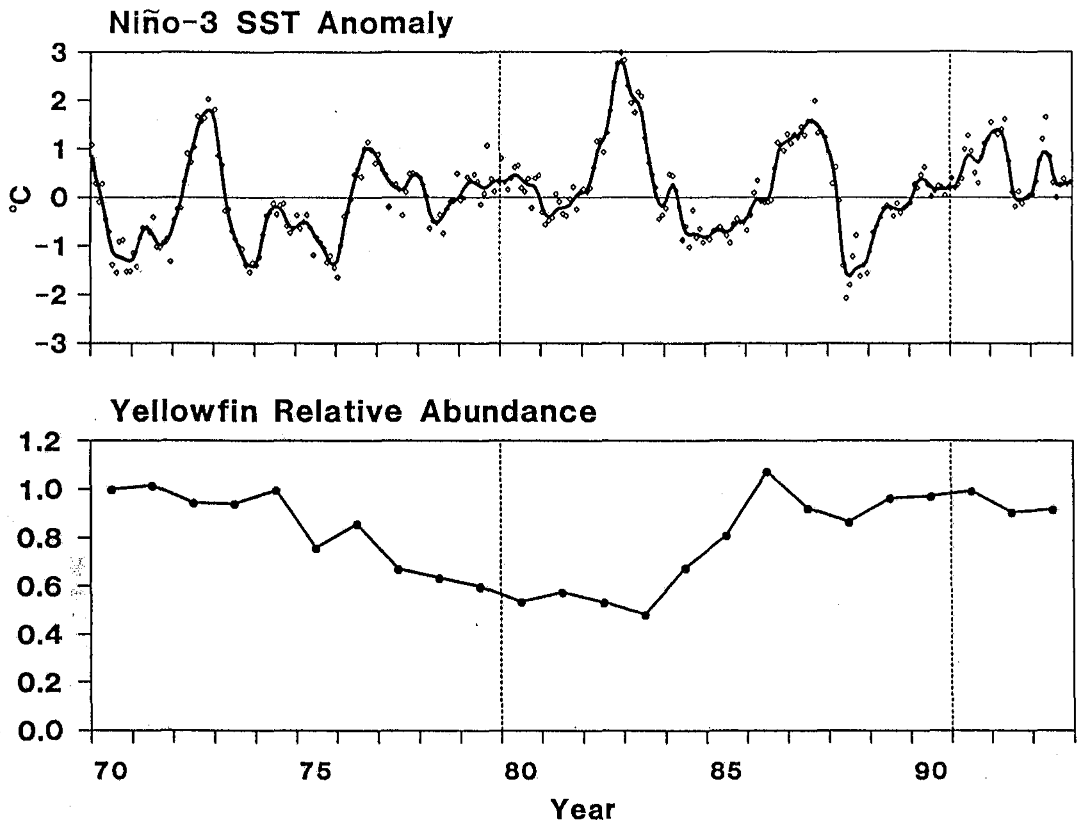

Figure 4. Interannual variability of the environment and yellowfin tuna abundance. (Top) Monthly Niño-3 SST anomaly (°C), in the eastern equatorial Pacific (5°S-5°N, 150°W-90°W), from NOAA/NWS/Climate Analysis Center. (Bottom) Annual relative abundance of yellowfin tuna in the eastern Pacific (from Bayliff, 1993, Figure 12). Dashed lines mark the period of this study (1980-1990).

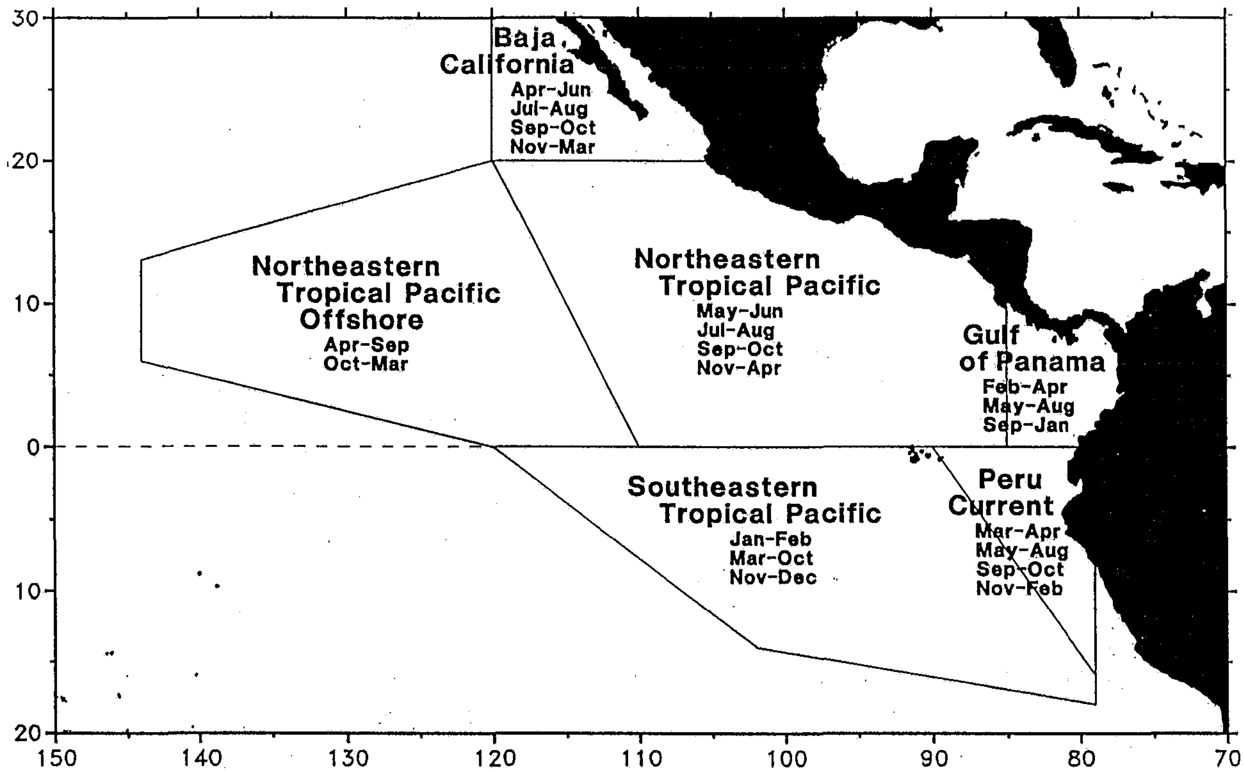

Figure 5. Season-areas used for standardization (from Punsly, 1987).

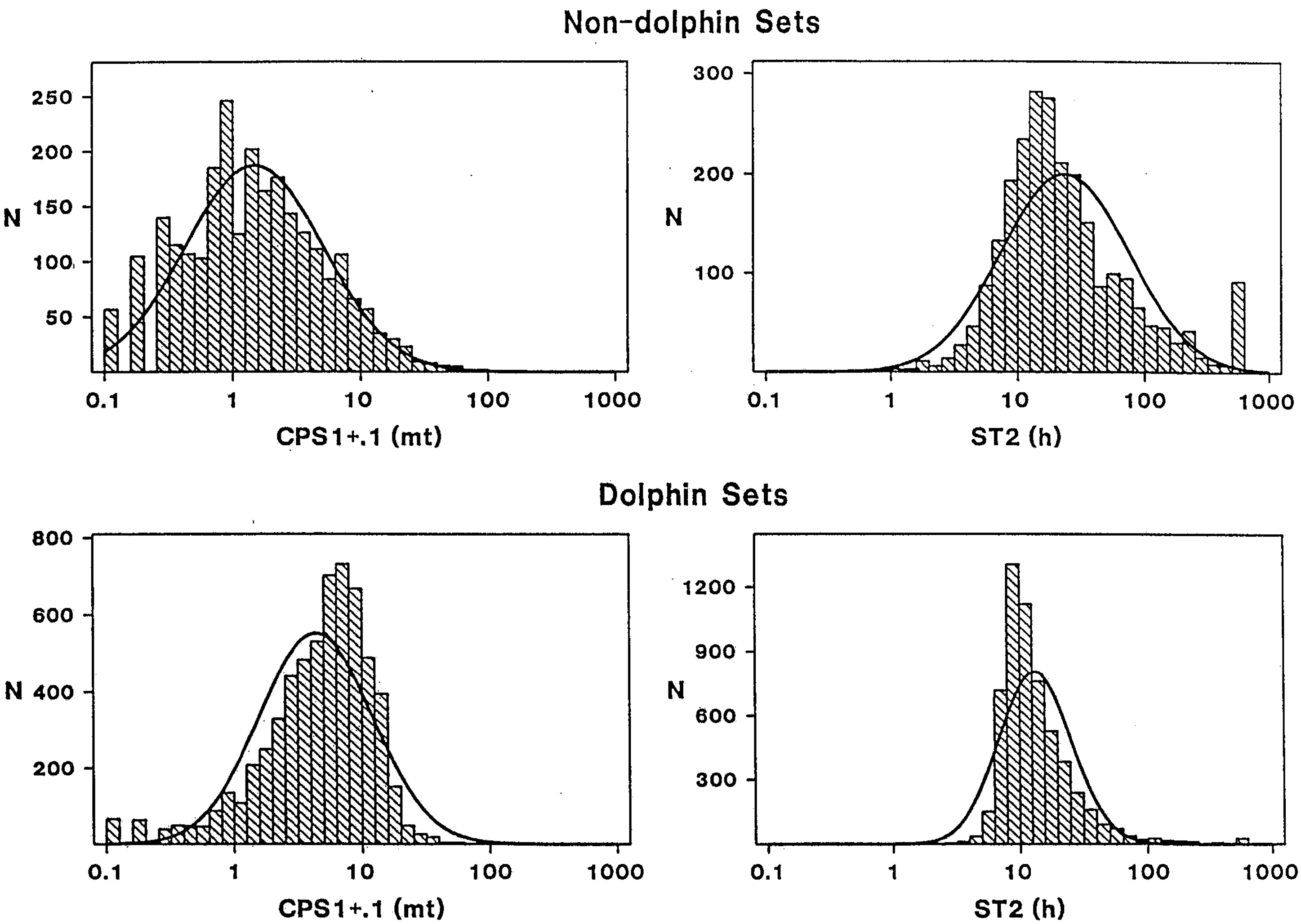

Figure 6. Frequency distributions of log-transformed yellowfin >7.5kg catch per set (CPS1, mt) and searching time (ST2, h) for non-dolphin and dolphin sets. N = number of 2°x2° quadrangle-month means for the 1980-1990 study period. Normal curves are defined by the observed means and standard deviations.

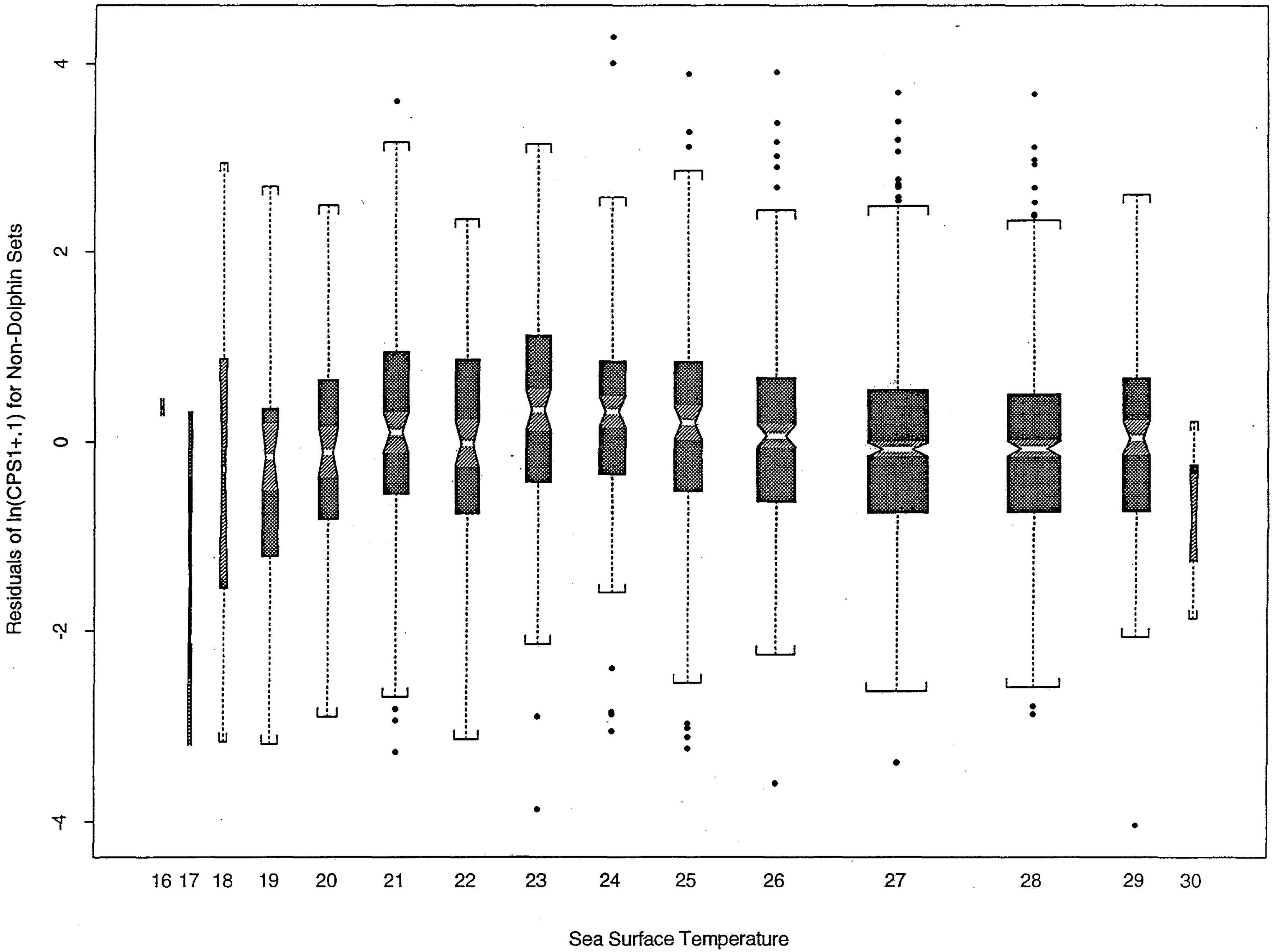

Figure 7. Box plot of residuals of ln(CPS1+0.1) versus sea-surface temperature for non-dolphin sets. Residuals come from a general linear model including the following significant factors: years, season-areas, vessel capacity, and percent skipjack. The tops, middles and bottoms of the boxes represent the upper quartiles, medians, and lower quartiles, respectively. Brackets denote the 95% confidence intervals. Dots represent outliers. The width of the boxes is proportional to the number of observations (2°x2° quadrangle-months).

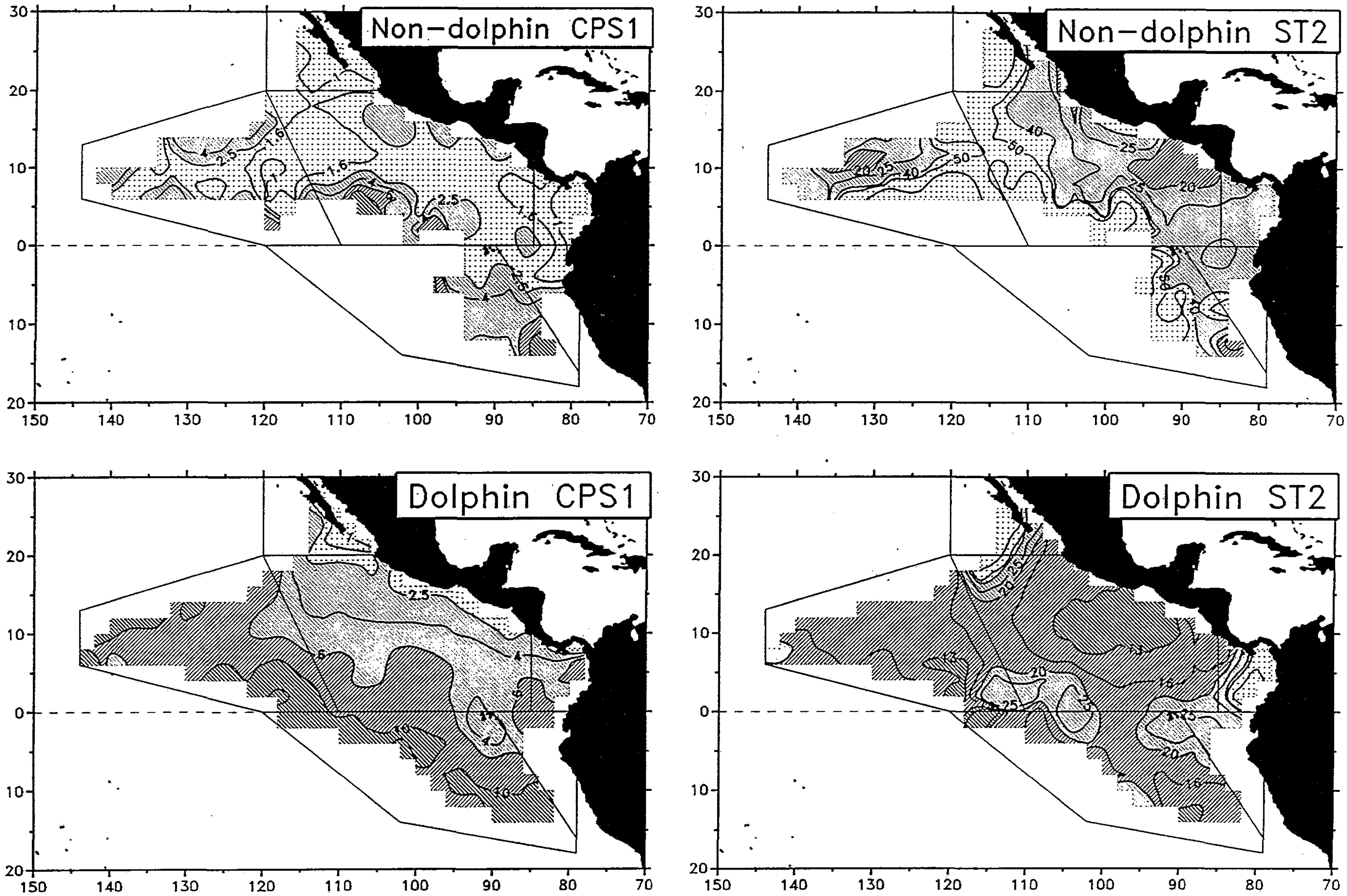

Figure 8. Average geographical distributions of yellowfin >7.5kg catches per set (CPS1, mt) and searching times (ST2, h) for non-dolphin and dolphin sets during 1980-1990. Thin lines mark purse-seine fishery areas used in the season-area classification.

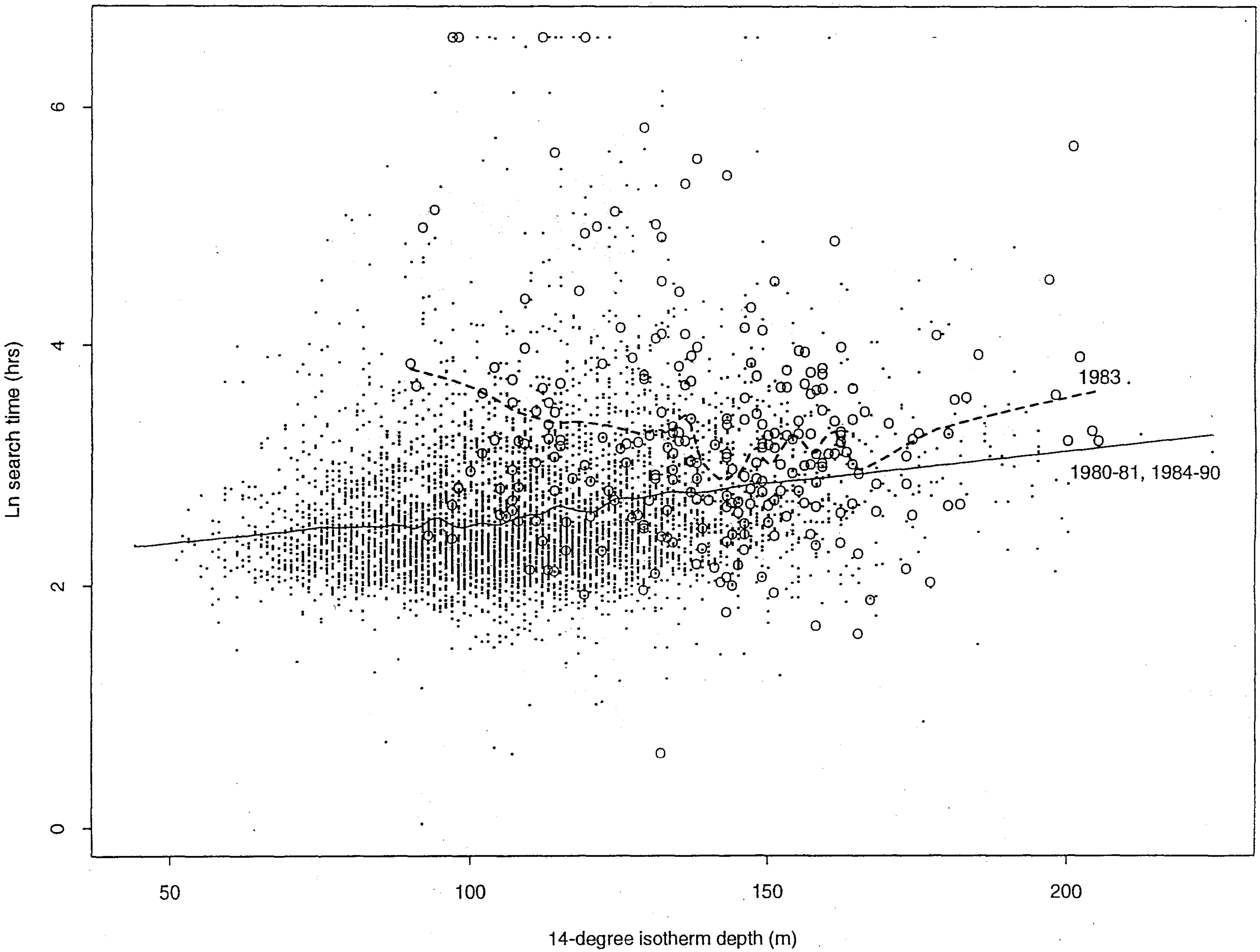

Figure 9. The effect of the 1983 El Niño on the relationship between dolphin-set searching time and the depth of the 14-degree isotherm. Each observation, open circles for 1983 and dots for other years, represents a 2°x2°-quadrangle-month. The dashed line shows the relationship during

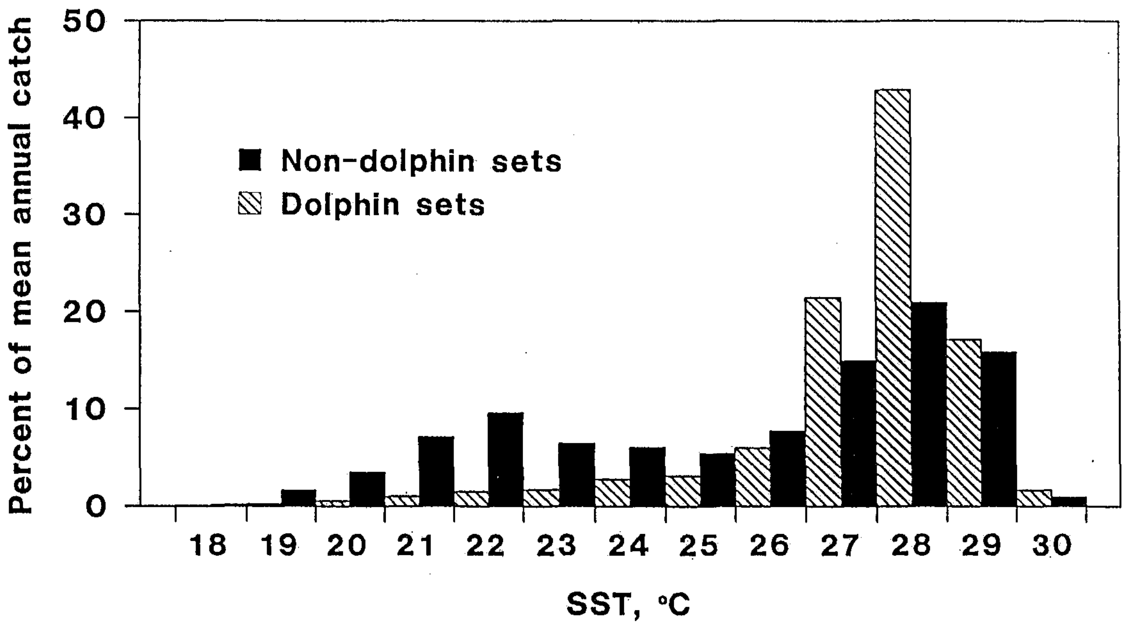

Figure 10. Percent frequency distributions of catch in weight of yellowfin >7.5kg by purse seiners versus sea-surface temperature (SST). The percentages for dolphin (solid bars) and non-dolphin (hatched bars) sets were estimated separately. The mean annual (1980-1990) catch from sets with sufficient data to use in the analysis was 18,219 mt for non-dolphin sets and 67,602 mt for dolphin sets.

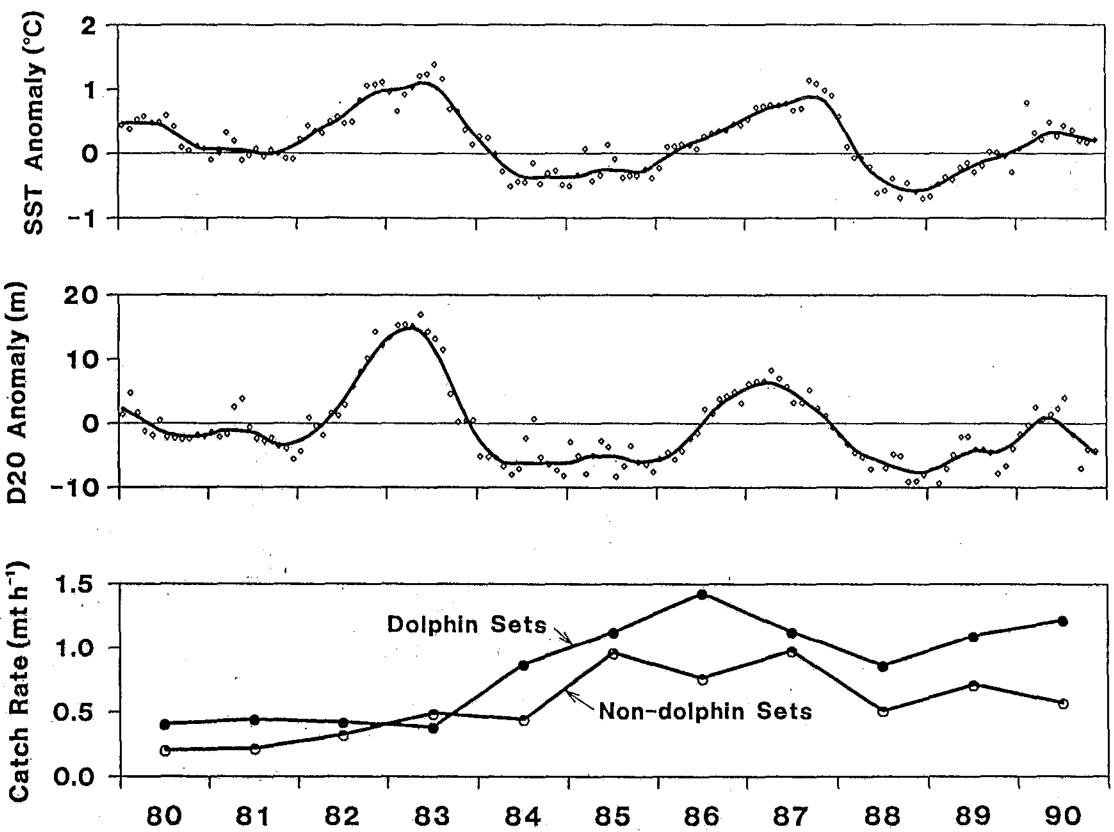

Figure 11. Interannual variability of monthly mean SST anomaly (top) and D20 anomaly (middle) in the eastern Pacific purse-seine tuna fishery area, and annual mean catch rate (CPS2/ST2, bottom) of yellowfin >7.5kg in non-dolphin and dolphin sets, excluding vessels >360 mt capacity and trips which caught less than 450kg yellowfin >7.5kg.

Table 1. Independent variables extracted from environmental databases and vessel logbooks.

Environmental Data

- SST, sea-surface temperature
- MLD, mixed layer depth
- D20, 20°C isotherm depth
- D14, 14°C isotherm depth
- TD, thermocline depth
- TT, thermocline temperature
- TS, thermocline strength
- TAUX, eastward pseudostress
- TAUY, northward pseudostress
- U, eastward wind speed
- V, northward wind speed
- TAU, scalar pseudostress
- WS, scalar wind speed
- UPW, upwelling index

Vessel Logbook Data

- SPD, speed
- CAP, capacity
- BRAD, bird radar
- HELI, helicopter
- NLEN, net length
- NDEP, net depth
- PSJ, percent skipjack
- PFO, percent floating object

Table 2. Numbers of bathythermograph profiles, after screening for errors and replicates, used to define habitat quality in monthly grids (1980-1990) and in climatologies (1960-1991). NODC = National Oceanographic Data Center CD-ROM NODC-03: Global Ocean Temperature and Salinity Profiles, vol. 2, Pacific Ocean; MOODS = Navy Master Oceanographic Observations Data Set, including non-NODC observations through 1983 obtained from the Naval Oceanographic Office through NODC and 1985-1990 observations obtained from the Joint Environmental Data Analysis Center of Scripps Institution of Oceanography; SOP = French-American ship-of-opportunity observations obtained from Pacific Marine Environmental Laboratory (PMEL; Kessler, 1990); NRIFSF = National Research Insitute of Far Seas Fisheries of Japan mechanical bathythermograph data obtained from PMEL and from National Ocean Service / Ocean Applications Branch.

	1980-1990	1960-1991
NODC	40,441	127,365
MOODS	9,045	15,077
SOP	2,463	11,305
NRIFSF	456	4,744
Total	52,395	158,491

Table 3. Percent of total sums of squares of log-transformed catch per set and search time for non-dolphin and dolphin sets explained by significant environmental, spatiotemporal, and vessel effects in general linear models.

	Catch per Set		Search Time	
	Non-Dolphin	Dolphin	Non-Dolphin	Dolphin
Environment	1.4	2.8	1.2	1.4
Season-Area	13.8	22.5	5.5	1.8
Year	13.9	11.0	11.2	14.8
Vessel	4.4	0.9	2.3	1.3
Total Explained	33.5	38.2	20.2	19.3

Table 4. Season-area mean catches per set (CPS1 and CPS2, mt), search times (ST2, h) and catch rates (CPS2/ST2, mt h^{-1}) for non-dolphin (ND) and dolphin (D) sets, excluding vessels with capacities <360 mt. Bold font indicates catch per non-dolphin set greater than catch per dolphin set, non-dolphin set search time less than dolphin set search time, or non-dolphin set catch rate greater than 90% of dolphin set catch rate.

Area Season	CPS1		CPS2		ST2		CPS2/ST2		
	ND	D	ND	D	ND	D	ND	D	ND/D
Southeastern Tropical Pacific									
Jan-Feb	12.4	16.9	15.5	17.3	23.1	17.6	0.74	1.08	0.68
Mar-Oct	8.9	17.3	17.2	18.4	**24.8**	**25.3**	0.76	0.8	**0.95**
Nov-Dec	12.7	18.0	16.4	18.5	29.9	23.0	0.60	0.88	0.68
Peru Current									
Mar-Apr	5.1	-	9.7	-	27.7	-	0.39	-	-
May-Aug	10.2	-	18.5	-	32.7	-	0.63	-	-
Sep-Oct	8.2	-	14.3	-	31.0	-	0.51	-	-
Nov-Feb	10.0	16.1	23.6	37.0	**26.0**	**40.7**	0.67	0.48	**1.41**
Gulf of Panama									
Feb-Apr	5.2	14.5	9.5	16.0	22.7	20.0	0.46	0.88	0.53
May-Aug	7.6	15.8	11.5	17.5	**21.2**	**29.5**	0.59	0.66	**0.91**
Sep-Jan	5.1	15.2	10.3	16.3	36.9	27.0	0.31	0.66	0.46
Northeastern Tropical Pacific									
May-Jun	5.5	11.2	11.3	12.6	31.1	16.5	0.40	0.84	0.47
Jul-Aug	6.5	9.7	**12.0**	**10.8**	26.8	16.1	0.49	0.74	0.67
Sep-Oct	9.2	12.8	13.2	13.3	25.1	14.8	0.58	0.99	0.59
Nov-Apr	7.1	11.3	**13.1**	**12.3**	25.9	16.4	0.56	0.82	0.67
Northeastern Tropical Pacific Offshore									
Apr-Sep	6.0	17.3	10.0	17.9	23.9	18.6	0.46	1.06	0.43
Oct-Mar	7.5	17.2	14.7	17.5	40.3	15.4	0.40	1.25	0.32
Baja California									
Apr-Jun	2.2	5.5	**8.2**	**7.6**	28.0	18.1	0.32	0.47	0.69
Jul-Aug	0.4	4.5	3.7	7.5	52.7	18.9	0.08	0.44	0.18
Sep-Oct	1.2	5.9	3.5	7.5	40.2	21.5	0.10	0.39	0.25
Nov-Mar	5.5	6.8	9.0	9.3	18.6	17.4	0.53	0.59	**0.91**

Table 5. Regression coefficients for significant environmental factors for general linear models of log-transformed catch per set (CPS1+.1) and search time (ST2) for non-dolphin and dolphin sets. Coefficients were standardized by significant vessel and spatiotemporal factors.

Factor	Catch per Set		Search Time	
	Non-Dolphin	Dolphin	Non-Dolphin	Dolphin
$(SST - SST_{opt})^2$	-0.209	-0.091	-	-
$(TT - 19)^2$	-	-	0.124	-
TT	-	-0.105	-	-
MLD	-	-	0.110	-
D14	-	-	-	0.090
$(TS - .25)^2$	-	0.122	-	-
TAU	-	0.051	-	-

Table 6. Regression coefficients from Table 5 back-transformed into original units.

Factor, units	Catch per Set		Search Time	
	Non-Dolphin	Dolphin	Non-Dolphin	Dolphin
$(SST - SST_{opt})^2$, °C^2	0.970	0.987	-	-
$(TT - 19)^2$, °C^2	-	-	1.017	-
TT, °C	-	0.895	-	-
MLD, m	-	-	1.010	-
D14, m	-	-	-	1.004
$(TS - .25)^2$, $(°C\ m^{-1})^2$	-	1.003	-	-
TAU, $(m^2\ s^{-2})$	-	1.001	-	-

Table 7. Analyses of variance of large yellowfin catch per set (ln(CPS1+.1)) by environmental, spatiotemporal, and vessel factors. Environmental and vessel factors are defined in Table 1.

Catch per Non-dolphin Set

	d.f.	SS	MS	F	Pr(F)
Environ.: $(SST-23)^2$	1	58.8	58.8	53.3	0.000000
Season-Area	19	575.4	30.3	27.5	0.000000
Year	10	576.3	57.6	52.3	0.000000
Vessel: CAP	1	77.8	77.8	70.5	0.000000
PSJ	1	104.2	104.2	94.5	0.000000
Residual	2506	2763.6	1.1		
Total	2538	4156.1			

Catch per Dolphin Set

	d.f.	SS	MS	F	Pr(F)
Environment: TT	1	45.9	45.9	78.1	0.000000
$(SST-26)^2$	1	29.8	29.8	50.8	0.000000
TAU	1	12.7	12.7	21.7	0.000003
$(TS -.25)^2$	1	70.3	70.3	119.6	0.000000
Season-Area	19	1282.5	67.5	114.9	0.000000
Year	10	629.3	62.9	107.1	0.000000
Vessel: SPD	1	7.3	7.3	12.5	0.000415
CAP	1	33.2	33.2	56.5	0.000000
BRAD	1	9.0	9.0	15.3	0.000095
Residual	6081	3573.4	0.6		
Total	6117	5693.5			

Table 8. Analyses of variance of large yellowfin search time (ln(ST2)) by environmental, spatiotemporal, and vessel factors. Vessel and environmental factors are defined in Table 1.

Non-dolphin Set Search Time

	d.f.	SS	MS	F	Pr(F)
Environ.: $(TT-19)^2$	1	21.4	21.4	18.8	0.000015
MLD	1	22.3	22.3	19.6	0.000010
Season-Area	19	194.0	10.2	9.0	0.000000
Year	10	391.4	39.1	34.5	0.000000
Vessel: SPD	1	55.6	55.6	49.0	0.000000
PSJ	1	24.0	24.0	21.1	0.000004
Residual	2468	2803.0	1.1		
Total	2501	3511.7			

Dolphin Set Search Time

	d.f.	SS	MS	F	Pr(F)
Environment: D14	1	34.7	34.7	102.7	0.000000
Season-Area	19	42.5	2.2	6.6	0.000000
Year	10	355.7	35.6	105.3	0.000000
Vessel: NDEP	1	10.9	10.9	32.1	0.000000
BRAD	1	9.9	9.9	29.3	0.000000
HELI	1	9.5	9.5	28.2	0.000000
Residual	5725	1934.5	0.3		
Total	5758	2397.7			

APPENDIX

SPATIOTEMPORAL-STRATIFICATION METHODS USED TO ANALYZE PURSE-SEINER CATCH RATES OF YELLOWFIN TUNA >16.5 POUNDS, WITH AND WITHOUT DOLPHINS, IN THE EASTERN PACIFIC OCEAN

by

R. G. Punsly and P. C. Fiedler

ABSTRACT

This report describes the spatiotemporal-stratification methods used in Punsly and Fiedler, *in prep*. In order to analyze the relationships between the catch rates of yellowfin >16.5 lbs, during 1980-1990, and various environmental and spatiotemporal factors, using general linear models, we stratified into the data into 2° x 2° quadrangle-months. The effect of this was to reduce the noise in the data and the number of observations. Since each data set had its own peculiarities, each was stratified by a different method. Catch-rate data were stratified using a modified locally weighted least-squared regression. Environmental data were stratified using a moving average smoothing technique. Vessel characteristics data were stratified by using the mean within the strata.

SPATIOTEMPORAL-STRATIFICATION METHODS USED TO ANALYZE PURSE-SEINER CATCH RATES OF YELLOWFIN TUNA >16.5 POUNDS, WITH AND WITHOUT DOLPHINS, IN THE EASTERN PACIFIC OCEAN

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CONTENTS

INTRODUCTION

On the average, about 60% of the yellowfin catch in the eastern Pacific Ocean (EPO) comes from dolphin-associated schools (Joseph, 1994). Dolphins are easier to detect than yellowfin because they are larger and more often break the surface of the water. Also, yellowfin associated with dolphins are less likely to escape while the net is being set because the dolphins can be herded back to the net and the tunas will follow. Consequently, yellowfin associated with dolphins have greater than average vulnerability to capture (Punsly *et al.*, 1994). In addition, Calkins (1965) found that yellowfin caught with dolphins tend to be larger (~40 lb average) than yellowfin from non-dolphin sets (~10 lb average), which, according to Punsly *et al.* (1994), results in a greater yield per recruit. Yellowfin schools not associated with dolphins ("non-dolphin schools") can be further classified as either free-swimming schools and schools associated with floating objects (Greenblatt, 1979). A 16.5-lb yellowfin is between the modes of dolphin and non-dolphin caught yellowfin (Figure 1). Also, larger yellowfin bring a greater price per unit of weight (National Marine Fisheries Service, 1992). Thus far, locating and capturing yellowfin associated with dolphins has been the most efficient fishing technique for yellowfin in the EPO.

Using sparse data, environmental factors, such as thermocline depth (Green, 1967; Anonymous, 1982, p 73-75), have been suggested to affect purse-seiner catch rates. Allen and Punsly (1984) found catch rates in 5°-quadrangle months to be affected by vessel characteristics, such as vessel speed and their association with dolphins. Punsly (1987) found that season-area combination, and their association with logs and skipjack also affected catch rates. Punsly and Fiedler (1996), using a resolution of 2°-quadrangle months, examined several environmental and spatiotemporal factors, hoping to find conditions under which purse seining has been relatively successful for yellowfin >16.5 lbs without dolphins.

The objective of this study is to develop and employ methods to stratify three types of data into 2°-quadrangle months: 1) catch-rate data, to be used as the dependent variable in the analyses, which is highly variable throughout time and space, 2) environmental data which is much less variable, and 3) vessel-characteristics data which are fairly constant well known. Locally weighted least-squares regression was used to remove the noise from the catch rate data. Environmental data were smoothed to fill in some gaps where fishing occurred. Vessel characteristics were calculated as the average in the strata.

MATERIALS AND METHODS

Logbook data

The principal source of data for catch, effort, and vessel characteristics is the IATTC logbook database, described by Orange and Calkins (1981), Punsly (1983), and Allen and Punsly (1984). This database has information on the daily fishing activities of about 90% of the purse seiners fishing for yellowfin in the eastern Pacific. Data for 20,000 to 50,000 sets are collected annually. The data used in this study included for each set, estimates of the weights, in short tons, of each species retained, location, starting and ending times, school type (free-swimming, dolphin-associated, or log-associated) and, for each trip, the vessel characteristics, holding capacity, speed, net dimensions, and the presence or absence of helicopters and bird radar. Many sources of error are possible, *e.g.*, recording the data in the logbooks, making abstracts of the logbooks, and transferring the information from the logbook abstracts into the computerized database. Logbook abstracts are routinely checked for detectable errors. For example, the sum of the estimates of the catches in weight of yellowfin plus skipjack in each set during a trip is compared to the weight unloaded. If they do not agree within 33% the data for the trip were not used. Also, the vessels' cruise tracks are plotted to detect recorded positions which are obviously erroneous. Then the data are corrected or omitted from the database.

Environmental data

We used bathythermograph and wind data to derive estimates of environmental variables (Table 1). The bathythermograph data were acquired from a variety of sources, including fishing, commercial, U.S. Navy and research vessels (Table 2). Mixed-layer depth (MLD), which represents the top of the thermocline, is defined as the depth at which temperature is 0.5°C less than surface temperature. In the tropical Pacific, the 20°C isotherm is typically near the middle of the thermocline (Kessler, 1990) and the 14°C isotherm is near the bottom of the thermocline (Meyers, 1979). Thermocline depth is defined as the depth of the maximum temperature gradient over 10-m intervals and thermocline strength as the magnitude of that gradient.

Temperature data were spatiotemporally stratified by month from 1980 through 1990, on a 2-degree latitude-longitude grid from 20°S to 30°N latitude and from the coast to 150°W longitude. Monthly coverage was low in some areas (Figure 2). Decorrelation scales, the distances required for a substantial change in surface temperature or thermocline depth, have been estimated as 3° latitude and 15° longitude in this region (Sprintall and Meyers, 1991). To ensure complete coverage of the fishery by the stratified data, these limits were relaxed slightly: at each grid point, means of all observations within 4° latitude and 20° longitude were calculated. The observations were weighted by the reciprocal of the distance from the grid point. A 2-month time window was allowed by including observations from the last half of the previous month and the first half of the following month, but weighted by 0.5. These large space and time windows allowed us to fill all data gaps, but probably smoothed over some real variability in coastal waters. We converted observations to anomalies (deviations from the monthly mean) before stratification to reduce the spatial variability of the observations. This procedure minimized bias caused by interpolation over or extrapolation into large data gaps. The bathythermograph data were identical, and the spatiotemporal stratification procedure we used was similar to that of Fiedler and Reilly (1994).

Monthly fields of surface-wind pseudostress (wind components multiplied by wind magnitude, $m^2\ s^{-2}$) were obtained from Florida State University. These 2° x 2° grids are smoothed over approximately the same spatial scales used for the bathythermograph data (Legler and O'Brien, 1988). Wind speed vectors and scalar (total) wind speed and pseudostress were derived from the pseudostress components. An upwelling index, equal to Ekman pumping velocity, was calculated from the divergence of horizontal Ekman transports (U, V) calculated as:

$$U = (\delta\tau_x + f\tau_y) / [\rho(f^2 + \delta^2)],$$
$$V = (\delta\tau_y - f\tau_x) / [\rho(f^2 + \delta^2)],$$

where τ_x and τ_y are the eastward and northward components of wind stress (calculated as pseudostress multiplied by a drag coefficient of 1.4×10^{-3} and an air density of 1.2 kg m^{-3}), ρ is water density (mt m^{-3}), f is the Coriolis parameter ($2\Omega\sin\Phi$), and δ is a frictional damping parameter ($\delta = [4.8\ d]^{-1}$) which balances wind forcing near the equator where f vanishes (Hsieh and Boer, 1992).

Climatological (1960-1991) fields of surface temperature, wind stress, thermocline depth, and thermocline strength are shown in Figure 3. These fields are means of monthly climatologies stratified from the same databases used for the monthly fields. The area in which the eastern Pacific purse-seine fishery operates is characterized by a strong, shallow thermocline and, in the heavily fished region between the equator and 20°N, warm surface water and converging trade winds. The cold-water tongue along the equator is the result of equatorial upwelling. The topography of the thermocline consists of two zonal ridges, along 10°N and the equator, and a general east-west slope from close to 40 m near the coast to 120 m at the offshore limits of the fishery. These patterns vary somewhat both seasonally and interannually (Fiedler, 1990).

Catch

The catch of yellowfin >16.5 lbs in each set was calculated by first estimating the number of fish in each semi-annual age group (see the discussion of the X and Y cohorts in Anonymous, 1993, p 66-69), using the method of Punsly and Deriso (1991), and then summing the average weights of fish from semi-annual age groups with monthly average weights greater than 16.5 lbs (which corresponds to an average length of 73 cm and an average age of approximately 18.5 months). $C_{jk} = \Sigma N_{ijk} W_{ik}$ for $W_{ik} > 16.5$ lbs, where C_{jk} is the catch of yellowfin >16.5 lbs in the jth set in the kth month, N_{ijk} is the estimated number of yellowfin in semi-annual age group i in set j in month k, and W_{ik} is the average weight of age-i yellowfin in month k. Because length-frequency samples (Tomlinson *et al.*, 1992) are available for only about 5% of the sets, estimates of N_{ijk} are based on frequencies from the sample(s) estimated to be the most similar (based on position, date, school type, and the presence or absence of skipjack) to set j in the logbook data (Punsly and Deriso, 1991). Because the method of Punsly and Deriso (1991) estimates age frequency, ages were converted to lengths by the relationship determined by Wild (1986). Lengths were then converted to weights by the formula provided by Hennemuth (1957).

Catch rates

Catch rate of yellowfin >16.5 lbs was defined as the weight (short tons) of yellowfin >16.5 lbs caught per hour of searching. The two basic theoretical components of catch rate are catchability and abundance: $CR = q\bar{N}$, where q is the catchability coefficient and $\bar{N}$ is the average abundance. We did not separate catchability from abundance because we are interested only in their product as a measure of success.

The two basic practical components of purse-seiner catch rates are the catch per set and the searching time between sets. Two measures of each component were examined separately to get a more precise understanding of how the environment influences catch rates. For the first analysis, catch rates of yellowfin >16.5 lbs by vessels targeting all sizes of fish were used, and for the second analysis the catch rates by vessels targeting mainly yellowfin >16.5 lbs were used.

The first pair of indices describes the 1980-1990 fishery, which targeted all sizes of fish. Search time, ST1, was defined as the number of hours searched between sets which yielded more than 3 tons of yellowfin of all sizes. Sets containing less than 3 tons are seldom made intentionally. We omitted them from the yellowfin catch rate analyses because they usually indicate unusual circumstances, such as some problems while making the set which result in most of the fish being lost (Allen and Punsly, 1984). Time spent in sets with less than 3 tons of yellowfin was not counted as search time. Data from aborted searches, usually resulting from breakdowns, bad weather, or a decision to run to another area, were not included in the analyses, because the times of day that these events occurred, which are needed to estimate searching times, were not recorded in the logbooks. Catch per set, CPS1, was defined as the weight of yellowfin >16.5 lbs landed in the set. CPS1 was zero if at least 3 tons small yellowfin were caught, but no yellowfin >16.5 lbs were estimated to have been caught.

The second pair of indices describes a fishery which targets mainly yellowfin >16.5 lbs. Search time, ST2, was defined as the number of hours searched between sets which yielded more than 1/2 ton (the resolution of the database) of yellowfin >16.5 lbs. Time spent in sets which produced less than ½ ton of yellowfin >16.5 lbs was not counted as search time. Also, data from aborted searches were not included in the analyses. The second index of catch per set, CPS2, is defined as the catch of yellowfin larger than 16.5 lbs from sets which produced at least ½ ton of yellowfin over 16.5 lbs. Therefore, CPS2 cannot be less than ½ ton. We chose to focus on CPS1 and ST2. CPS1 was preferred over CPS2 because zero catch-per-set data are useful for determining which are the wrong conditions for catching yellowfin >16.5 lbs. ST2 was preferred over ST1 because ST2 is a better measure of the time needed to locate yellowfin >16.5 lbs. Overall catch rate was defined as CPS2/ST2, which was a measure of the success of vessels targeting mostly yellowfin >16.5 lbs.

Catch rate data (ln(CPS1 + 0.1) and ln(ST2)) from 1980-1990 were stratified into 2° x 2° quadrangle-months, using locally weighted least squares regressions (Cleveland and Devlin, 1988) to estimate the values at the midpoints of each quadrangle-month. The logarithmic transformations were applied because: 1) the data were distributed lognormally (Punsly, 1987) and 2) a multiplicative model is preferable for standardization (Allen and Punsly, 1984). Mean positions during each search were used for search-time analyses, while set positions were used for the catch-per-set analysis. Then we used the method of Punsly and Deriso (1991), except that: 1) we used 2° x 2° quadrangles and 2) we did not need to add a minimum observed value to the ln(CPS1 + 0.1) data, because no serious edge effects were detected for catch per set. However, to reduce the effect of shorter search times near the edges of the fishery being extrapolated to even shorter search times outside the fishery, an observation with the maximum observed search time (ln(ST2) = 6.59)) was added to each quadrangle-month which had all of the data points on one side of the cell, in latitude, longitude, or month. The weights of these added observations were set equal to one minus the sum of the weights of the actual observations in the neighborhood, as in Punsly and Deriso (1991). The neighborhood included quadrangle-months within 3 units of time-distance, where 2° latitude, 2° longitude, and one month each equal a unit. If the estimates of either ln(ST2) or ln(CPS1 + 0.1) were greater than the maximum or less than the minimum observed value in the neighborhood, then the maximum or minimum was assigned respectively to the quadrangle. The ln(ST2) and ln(CPS1 + 0.1) data were stratified separately for dolphin and non-dolphin sets into each 2° x 2° quadrangle-month during 1980-1990.

Vessel characteristics

Vessel characteristics data were also stratified into 2° x 2° quadrangle-months for inclusion in the analyses. Stratification was done by calculating the mean of each of the following vessel characteristics in each 2° x 2° quadrangle-month (Table 1). Catch-per-set analyses included percent of sets by boats with helicopters, percent of floating-object sets, mean vessel speed weighted by number of sets, mean vessel fish-holding capacity weighted by number of sets, percent of sets by boats with bird radar, percent of yellowfin sets containing some skipjack, mean net length, and mean net depth, both weighted by number of sets. Search-time analyses included the percent of search time by boats with helicopters, percent of search time leading to floating-object sets, mean vessel speed weighted by search time, mean vessel capacity weighted by search time, percent of search time by boats with bird radar, and percent of search time leading to mixed yellowfin plus skipjack sets.

DISCUSSION

Three methods of spatiotemporal stratification were applied to three types of data, to produce 2°-quadrangle-month estimates. Yellowfin catch-rate data, which included catch per set and searching time for both dolphin and non-dolphin sets, were stratified by locally weighted least-squares regression. Environmental data, which included sea-surface temperature, thermocline temperature, thermocline depth, thermocline strength, mixed-layer depth, 14°- and 20°-isotherm depths, estimated temperature at the bottom of the net, an upwelling index, and wind speed and stress data, were moving averages over time and space. Vessel characteristics data such as vessel size and speed, net length and depth, percent of log- and skipjack-associated sets, percent of bird radar, were stratified by using the averages from observations within each stratum. Additional data and spatiotemporal stratification methods are still being explored. Hopefully, this will reaffirm any inferences made from the data and methods available at the time of this project.

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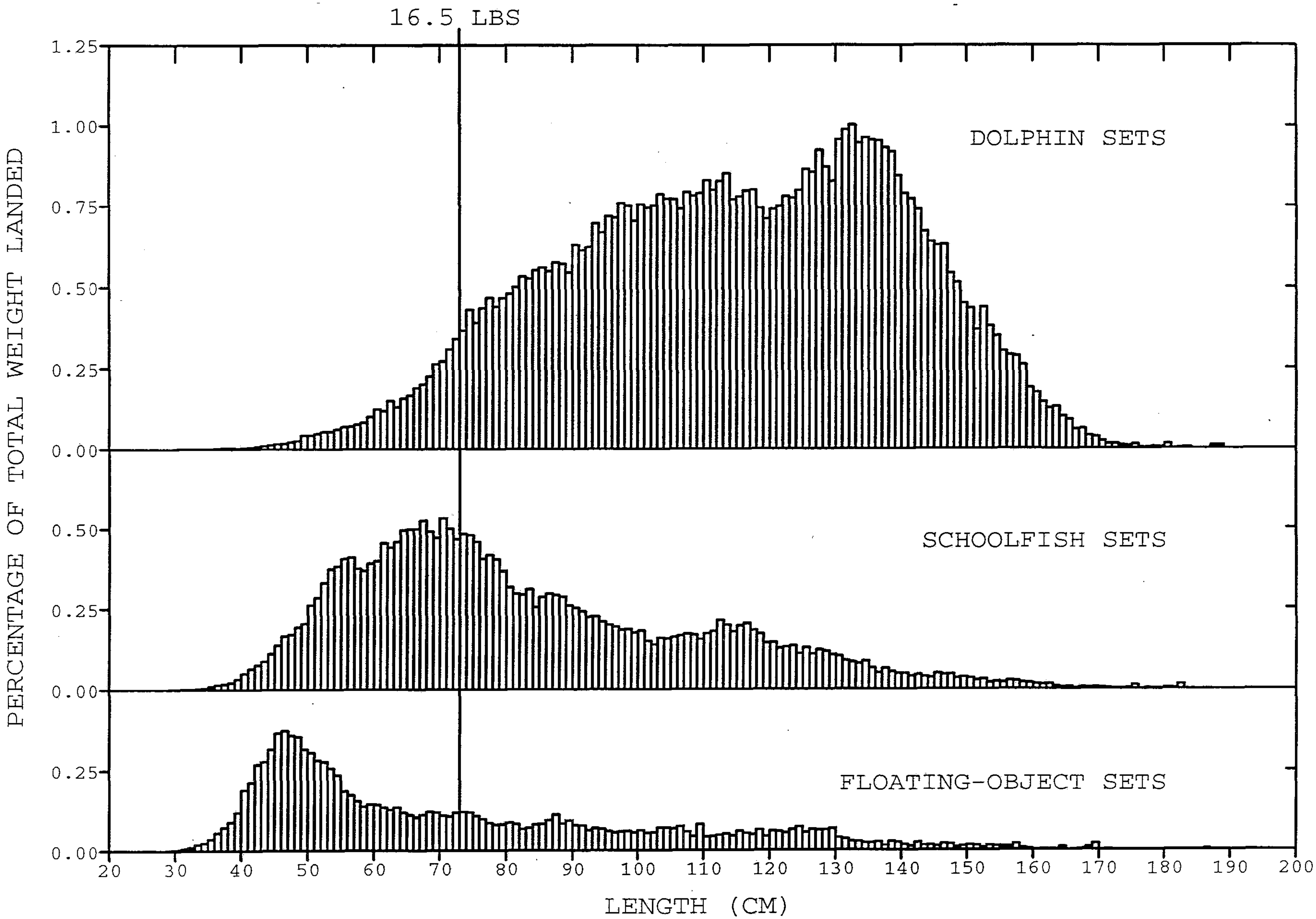

FIGURE 1. Estimated percent of weight of yellowfin tuna caught by purse seiners in the eastern Pacific Ocean, during 1980-1990, provided by Patrick K. Tomlinson, IATTC. During this time period dolphin, schoolfish, and floating-object sets provided 62.8, 25.4, and 11.8 percent of the catch, respectively.

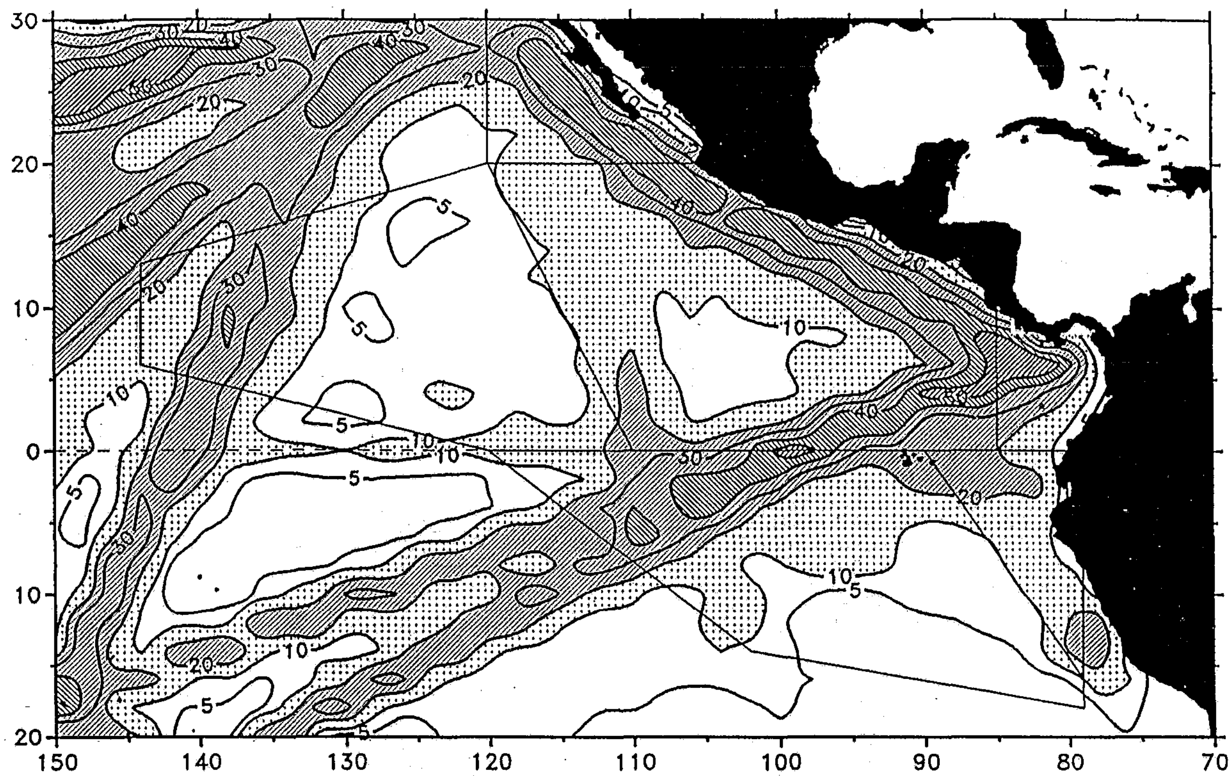

FIGURE 2. Percent monthly coverage of bathythermograph data in monthly 2° x 2° quadrangles, 1980-1990. Thin lines mark purse-seine fishing areas used in the season-area classification.

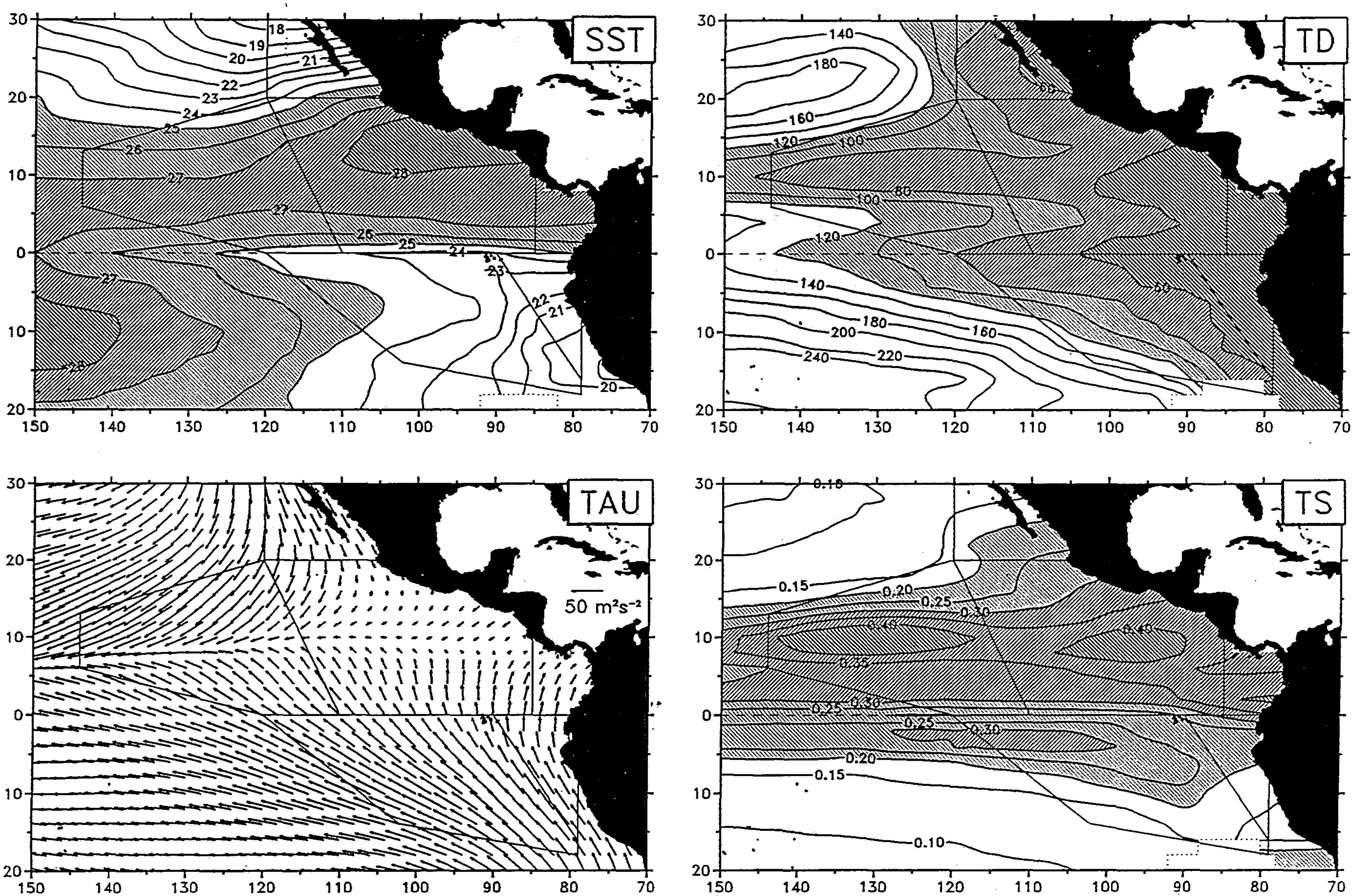

FIGURE 3. Climatological (1960-1991) fields of mean sea-surface temperature (SST, °C), thermocline depth (TD, m), wind pseudostress (TAU, m^2 s^{-2}), and thermocline strength (TS, °C m^{-1}). Thin lines mark purse-seine fishery areas used in the season-area classification.