Atlantic Skipjack Tuna: Influences of Mean Environmental Conditions on Their Vulnerability to Surface Fishing Gear

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Introduction

Of those tunas which are exploited commercially in the Atlantic, only the skipjack tuna, *Katsuwonus pelamis,* appears presently exploited at a level below that corresponding to maximum sustainable yield (Matsumoto, 1974). As a result, further increases in fishing effort by the international fleet may logically be directed toward this species. Realization of an economic return from such increased effort is complicated by the fact that the skipjack tuna is a fast swimming, wide ranging species (Kearney, 1976) which inhabits much of the tropical and subtropical Atlantic. Its availability by area and time varies greatly and it is only under certain conditions that skipjack tuna are sufficiently concentrated for economic harvest by surface gear (troll, pole and line, and purse seine).

Researchers and fishermen alike have long sought to improve the harvest of skipjack tuna by attempting to identify areas of high concentration. For fishermen this effort has taken the form of increased scouting activity over larger and larger areas. For researchers it includes identifying those areas where skipjack tuna forage is plentiful (Brandhorst, 1958; Blackburn and Laurs, 1972), ascertaining migration patterns of skipjack tuna (Rothschild, 1965; Fink and Bayliff, 1970; Williams, 1972), and defining preferred skipjack tuna habitat or habitat constraints as inferred from physical environmental indicators (Ingham, 1970; Ingham et al., 1977; Barkley et al., 1978; Sharp, 1979).

The approach of using physical environmental indicators to infer habitat limits of skipjack tuna appears preferable to habitat forecasts based on skipjack tuna forage or migration patterns because of the limited data available to assess these factors. In contrast, a comparatively large amount of physical oceanographic data is available for comparison with catch statistics since oceanographic observations are routinely made for other purposes.

Physiological experiments on captive skipjack tuna from the Pacific have been carried out to ascertain habitat preference as functions of several environmental indicators (Dizon, 1977; Dizon et al., 1977, 1978). No attempt has been made to integrate existing environment/habitat relationships and data with Atlantic catch data to define those areas where skipjack tuna should be available to surface gear. This paper attempts to do this and, in doing so, to develop working hypotheses for identifying areas of potential skipjack tuna concentration as an aid to exploiting and managing the resource.

ABSTRACT—Pertinent data and literature are examined to determine the effects of the environment on the spatial distribution of skipjack tuna, Katsuwonus pelamis, *in both the Atlantic and Pacific Oceans. Environment/skipjack distribution relationships derived from this information are applied to long-term annual mean distributions of dissolved oxygen and thermal structure for the Atlantic Ocean between lat. 40°N and 40°S. The depth of skipjack habitat is mapped. Within the defined habitat areas, high vulnerability of skipjack tuna to surface gear is inferred and areally compared with the long-term catch of the FIS (French, Ivory Coast, and Senegalese) fleet to confirm the validity of this approach. This technique is then used to hypothesize areas of vulnerability of skipjack to surface gear outside the range of the FIS fleet effort in the western Atlantic. Finally, the effects of surface winds on fishing operations are discussed and those areas where wind speed may hamper operations are outlined for the Atlantic Ocean between lat. 30°N and 30°S.*

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Environmental Constraints on Habitat

Temperature

Through the years researchers have attempted to use environmental parameters to define the distribution limits of skipjack tuna or to infer skipjack tuna-preferred habitat areas. Data on water temperature and most notably sea surface temperature has received greatest attention. Both Blackburn (1965) and Nakamura (1969) indicated that distribution limits for skipjack tuna can be defined using sea surface temperature. Laevastu and Rosa (1963) indicated worldwide occurrence of skipjack tuna is confined to the 17°-28°C range and that major skipjack tuna fisheries are found in the 19°-23°C range. More recently, Williams (1970) stated that adult eastern tropical Pacific skipjack tuna are most numerous at sea surface temperatures between 20° and 29°C. Miller and Evans[1] found that for 86 successful purse seine sets made on skipjack tuna in the eastern tropical Pacific, sea surface temperatures ranged from less than 20° to 30°C, with a pronounced mode at about 28.4°C (Fig. 1). Barkley et al. (1978) drew upon test data for captive skipjack tuna presented in Neill et al. (1976) and Dizon et al. (1977) to hypothesize that the habitat of Pacific skipjack tuna is confined to water temperatures equal to or greater than 18°C.

Another temperature related parameter which has been used to define skipjack tuna habitat limits is the depth of the isothermal or mixed layer. Green (1967) related the depth of the eastern tropical Pacific mixed layer to tuna purse seining success (Fig. 2A). Blackburn and Williams (1975) indicated that areas of high apparent skipjack tuna abundance in the eastern tropical Pacific are limited to areas where the mixed layer is less than 40 m deep. Miller and Evans (footnote 1) have examined the depth of the mixed layer and find that successful eastern tropical Pacific skipjack tuna sets are limited to mixed-layer depths of less than 85 m. Their findings show a pronounced mode for purse seine set success at 15 m (Fig. 2B) as well as a relation between skipjack tuna purse seine success and thermocline gradient (not shown).

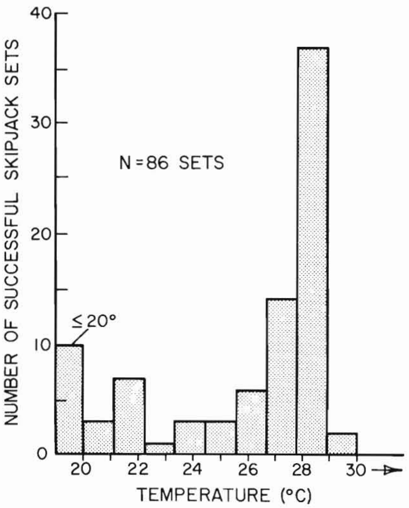

Figure 1.—Distribution of successful eastern tropical Pacific purse seine sets on skipjack tuna as a function of sea surface temperature (from Miller and Evans, footnote 1).

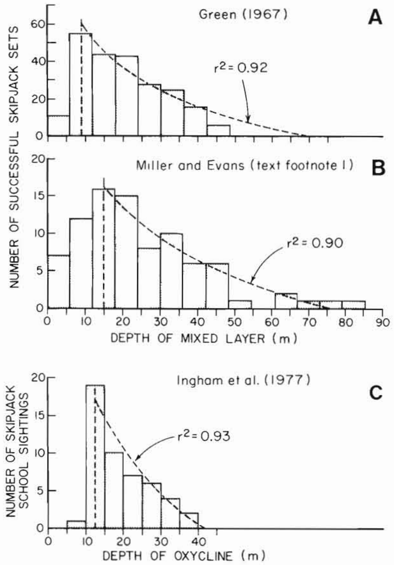

Figure 2.—Distribution of skipjack tuna school sightings and numbers of successful skipjack tuna purse seine sets as functions of the depths of the oxycline and mixed layer, respectively. A log curve has been fitted to the intervalized data to the right of the mode in each case.

Dissolved Oxygen and Salinity

Dissolved oxygen concentration has also been used to define skipjack tuna habitat. Barkley et al. (1978) have drawn on the work of other researchers to propose 3.5 ml/l as the minimum concentration of dissolved oxygen routinely tolerated by Pacific skipjack tuna. Ingham et al. (1977) found the depth of the 3.5 ml/l oxygen surface in the eastern Atlantic was related to surface skipjack tuna school sightings (Fig. 2C). Dizon (1977) indicated that captive skipjack tuna do not respond to rather drastic changes in salinity, but York (1969) has used salinity with some success in New Zealand as an "indicator" of areas of increased skipjack tuna availability. The increase in availability found by York is probably due to the presence of ocean fronts and/or convergence zones as indicated by variations in the distribution of salinity rather than by direct effects of salinity on the behavior of skipjack tuna.

Forage

Forage of skipjack tuna has been examined relative to skipjack tuna abundance. Dragovich (1970) examined the stomach contents of skipjack tuna caught by pole and line, longline, trolling, and purse seine in the eastern and western tropical Atlantic. Blackburn and Laurs (1972) used data collected during the EASTROPAC (Eastern

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[1] Miller, F. R., and R. H. Evans. The ocean environment of the eastern tropical Pacific as related to tuna purse seining. In prep.

Tropical Pacific) experiment to map the distribution of skipjack tuna forage in the eastern tropical Pacific. Blackburn and Williams (1975) found eastern tropical Pacific skipjack tuna distribution correlated with the nighttime concentration of skipjack tuna forage.

Weather

The marine environment can affect the efficiency of the fishing operation and, as a result, skipjack tuna vulnerability. Yuen (1959) indicated that cloudiness is correlated with the ability of fishermen to spot surface or near-surface skipjack tuna schools. Miller and Evans (footnote 1) found purse seine operations severely hampered when wind speed exceeds 8 m/second, with no successful sets made where wind speeds exceed 11 m/second (Fig. 3).

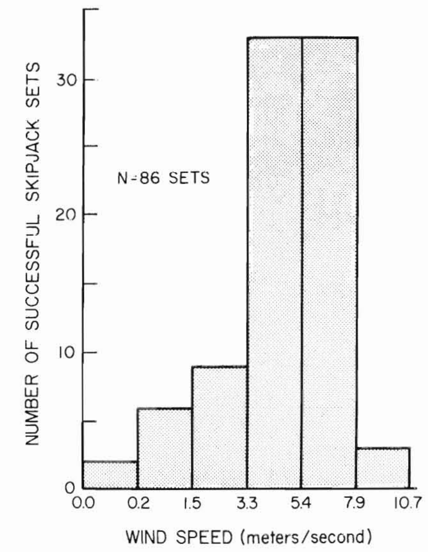

Figure 3.—Distribution of successful eastern tropical Pacific purse seine sets on skipjack tuna as a function of wind speed (from Miller and Evans, footnote 1).

Data Processing and Analysis

An examination of the methods used by previous researchers and the availability of pertinent Atlantic environmental data indicates that the approach taken by Barkley et al. (1978) is well suited to defining skipjack tuna habitat over large areas. Their method, developed from work done on Pacific skipjack tuna, uses the shallower of either the 18°C isotherm or the 3.5 ml/l dissolved oxygen surface as the skipjack tuna habitat lower boundary. Since Ingham et al. (1977) have used the 3.5 ml/l depth with success to define Atlantic skipjack tuna habitat limits, it was felt that this concentration was appropriate. Using only the depth of the 18°C isotherm as per Barkley et al. (1978), presents a problem as water temperature tolerance by skipjack tuna is size specific. They stated that all skipjack tuna have a lower boundary of 18°C but that the upper boundary for 40 cm (1.15 kg) fish is about 29°C while the upper boundary for 70 cm (7.34 kg) fish is about 23°C. Since 40 cm skipjack tuna are the smallest animals consistently taken in western Atlantic commercial catches (Coan, 1976), it was decided to set upper and lower thermal habitat boundaries for this study at 29° and 18°C, respectively. Since the sea surface temperature in this study is almost always less than 29°C (Fig. 4), this means the habitat of skipjack tuna would extend from the sea surface to the depth of either the 18°C isotherm or the 3.5 ml/l surface, whichever is shallower.

Data utilized herein were collected from a number of sources. Sea surface temperature contours were prepared from surface synoptic marine weather data, archived by the Fleet Numerical Oceanography Center (FNOC), Monterey, Calif. To prepare these data for analysis, sea surface temperature values for the period March 1971 to March 1979 were extracted, edited, checked for errors, and averaged by month and 1° square for the Atlantic Ocean between lat. 40°N and 40°S. An annual mean field for the same area was then created by taking the mean of the 12 monthly means for each 1° square. This annual mean sea surface temperature field was then computer smoothed and contoured (Fig. 5).

The depth of the 18°C isotherm was computed from data in two data files: 1) The Bauer-Robinson Numerical Atlas data file[2], File A, and 2) the National Oceanographic Data Center (NODC) station data format two (SD2) file (NODC, 1973), File B. File A for the Atlantic north of lat. 5°S contained water temperature data derived from all available mechanical bathythermograph, expendable bathythermograph, and hydrocasts taken prior to 1976. These data were organized by 1° square averages, by month, for water temperature, tabulated at 30 m intervals from the sea surface to 150 m. Below 150 m, File A contained data summarized at standard hydrocast levels. For each 1° square in File A, the mean depth of the 18°C isotherm was calculated using linear interpolation between the tabulated data points.

For areas south of lat. 5°S, File B, containing unsummarized hydrocast data, was used. For each File B hydrocast, the depth of the 18°C isotherm was computed by linear interpolation between observed levels. These values were then summarized by 1° square and month. The two mean fields derived from Files A and B were then merged and treated as was sea surface temperature to create an annual mean contour plot of the depth of the 18° C isotherm (Fig. 6).

The depth of the 3.5 ml/1 dissolved oxygen surface was extracted from File B for the area in the Atlantic Ocean between lat. 40°N and 40°S using linear interpolation methods similar to those used to

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[2] Made available by Compass Systems, Inc., San Diego, Calif. Mention of trade names or commercial firms does not imply endorsement by the National Marine Fisheries Service, NOAA.

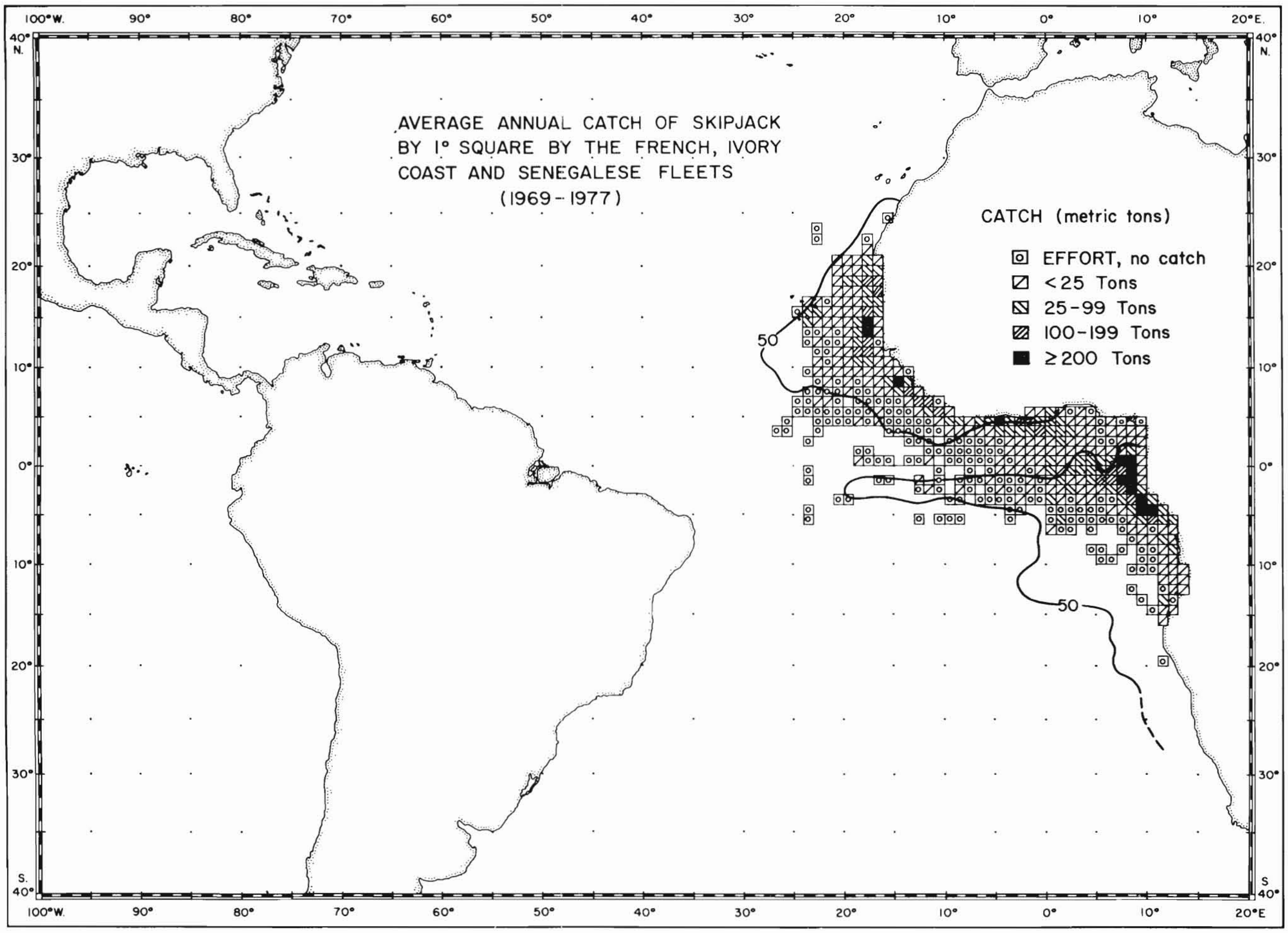

Figure 4.—Distribution of average annual catch of skipjack tuna by 1° square by the French, Ivory Coast, and Senegalese fleets (1969-77). The 50 m skipjack tuna habitat depth contour has been superimposed.

extract the 18°C isotherm (Fig. 7).

Contours of skipjack tuna habitat depth (Fig. 8) were created by analyzing a data field derived from graphically integrating the depths of the 18°C isotherm (Fig. 6) and the 3.5 ml/l dissolved oxygen surface (Fig. 7). Mean total catch in metric tons (t) by 1° square for the French, Ivory Coast, and Senegalese (FIS) fleet were extracted from ICCAT (International Commission for the Conservation of Atlantic Tunas) data bases for 1969 through 1977 (Fig. 4). These data were summed for all years, averaged, and plotted by 1° square. Those areas where fishing effort occurred in any year but where no catch was recorded were so noted.

Contours of surface, vector, mean wind speed were extracted from monthly contour plots in Hastenrath and Lamb (1977). Annual mean wind speed for the area lat. 30°N to 30°S in the Atlantic was obtained from their data by plotting monthly isotachs and then abstracting an envelope which contained all 12 monthly wind speed contours (Fig. 9). The contours presented are therefore not contours of mean wind speed but are annual, areal, composite ranges of the individual vector, mean wind speeds. Vector mean wind speed values equal to or greater than the contour value would be expected within all areas encompassed by a particular isotach (Fig. 9) at some time during the year but not necessarily during all months.

Discussion

Traditionally, surface fisheries for Atlantic skipjack tuna have been largely confined to eastern tropical areas for which representative catch-effort data are available. No such time series of catch-effort data exists for the more localized fishing areas of the western Atlantic and an alternate method of identifying

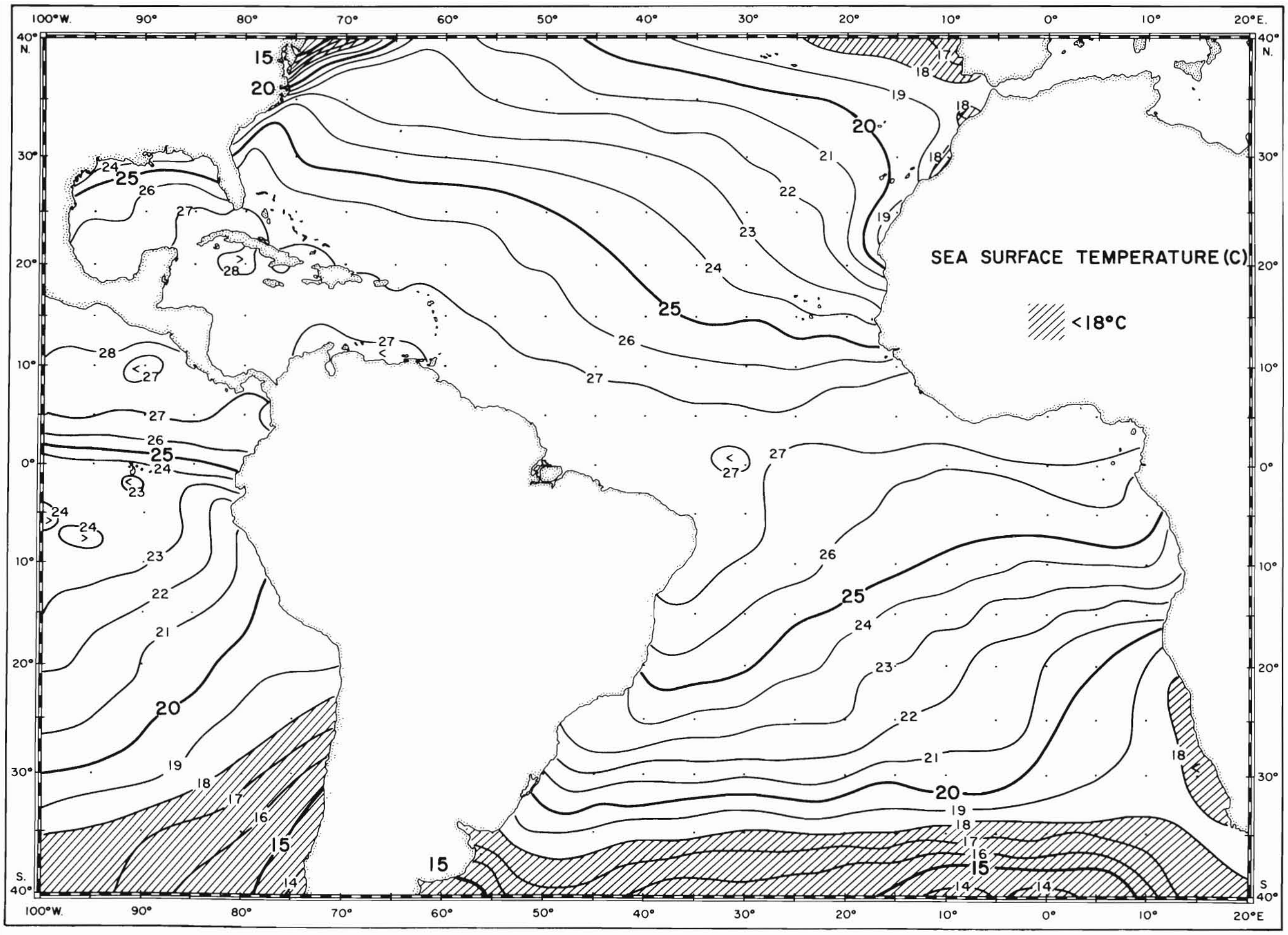

Figure 5.—Long-term annual mean sea surface temperature field, 1971-79. Hatched areas are colder than 18°C.

probable areas of skipjack tuna availability is required. Such an approach would be to identify areas suitable for skipjack tuna habitation. Previously described criteria of Barkley et al. (1978) (those regions confined within the 3.5 ml/l and 18°C surfaces) were used to define areas suitable for skipjack tuna habitation in the Atlantic between lat. 40°N and 40°S.

In using the 18°C isotherm as a lower thermal boundary for skipjack tuna habitat, there are some areas of the Atlantic where the entire water column is colder than this value. Those areas, which are shown to contain no skipjack tuna habitat, are readily apparent in the sea surface temperature field (Fig. 5). They include: 1) Almost all of the Atlantic south of lat. 34°S, 2) the area of strong upwelling of cold waters along the coast of southwest Africa between lat. 20°S and 34°S, 3) two smaller upwelling areas off the northwest coast of Africa, 4) the water northwest of Portugal, and 5) the waters off the east coast of the United States north of the Gulf Stream.

Remaining areas having surface temperatures in excess of 18°C are potential skipjack tuna habitat areas. Examination of habitat depth as defined by 18°C isotherm (Fig. 6) shows habitat depth is shallowest in the eastern Atlantic, increasing gradually toward two depth maxima located near the centers of the subtropical gyres in the north and south Atlantic. These areas of maximum thermal habitat depth are separated by a ridge of shallower depth located between the Equator and lat. 10°N caused by equatorial upwelling. Several of the areas of shallowest thermal habitat off northwest and southwest Africa and the area off the south coast of Brazil are coincident with areas of coastal upwelling.

Depth contours of the 3.5 ml/l dissolved oxygen surface (Fig. 7),

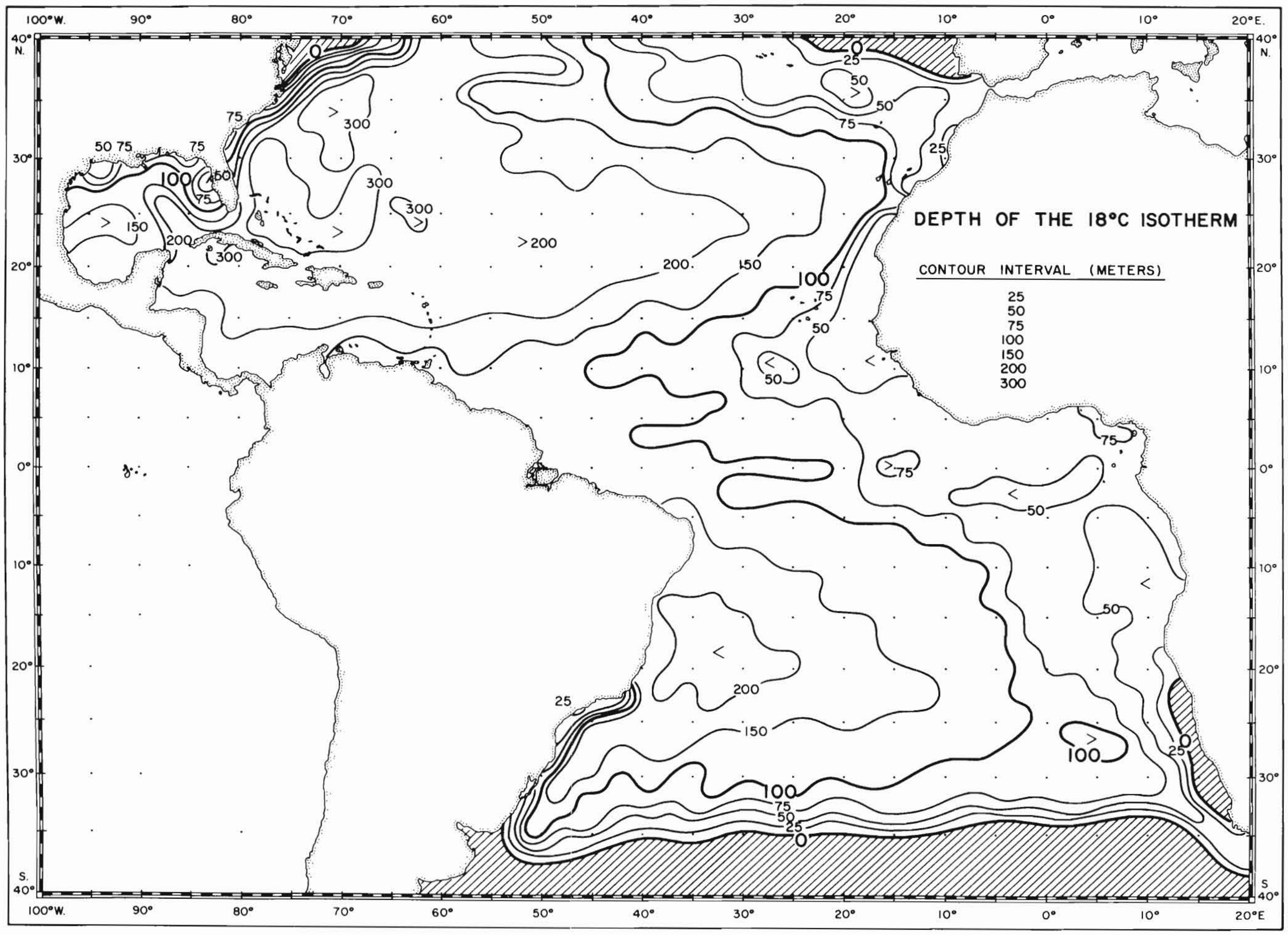

Figure 6.—Long-term annual mean depth of the 18°C isotherm. Hatched areas are colder than 18°C at all depths.

the second habitat constraining parameter, display similar large-scale features. As with the depth of the 18°C isotherm, the 3.5 ml/l surface is shallow in the eastern Atlantic, becoming deeper to the west. This layer also deepens poleward from the tropics due to higher dissolved oxygen capacity of colder water. A trough in the 3.5 ml/l surface symmetric about the Equator appears to be associated with the equatorial undercurrent. As with the 18°C isotherm, coastal upwelling causes shoaling of the 3.5 ml/l surface in the areas off southwest and northwest Africa and southern Brazil. For the areas off Argentina, northern Brazil, and Venezuela, shoaling of the 3.5 ml/l surface may not be caused by upwelling in the immediate area but rather by an increase in primary productivity associated with the advection of upwelled waters out of the source area[3].

In nearshore areas high rates of primary production associated with upwelled waters inhibit light penetration. This causes a decrease in the compensation depth which in turn causes a shoaling of the near surface dissolved oxygen maximum (footnote 3) and the 3.5 ml/l surface. Advection of surface waters, and to some extent turbulent mixing, may transport nutrient-rich surface water out of the upwelling area. An example of this would be the shoal area (less than 50 m) of the 3.5 ml/l surface extending into the Atlantic from the coast of Brazil near lat. 20°S. Mascarenhas et al. (1971) indicated significant coastal upwelling as well as large cyclonic and anticyclonic eddies in this area. These findings agree with those of Reid et al. (1977) who stated that a substantial poleward flow exists just offshore of the Brazil current. These mechanisms could combine to advect substantial quantities of nutrient-rich surface water, off-

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[3] See pages 85-86 in Parsons and Takahashi (1973).

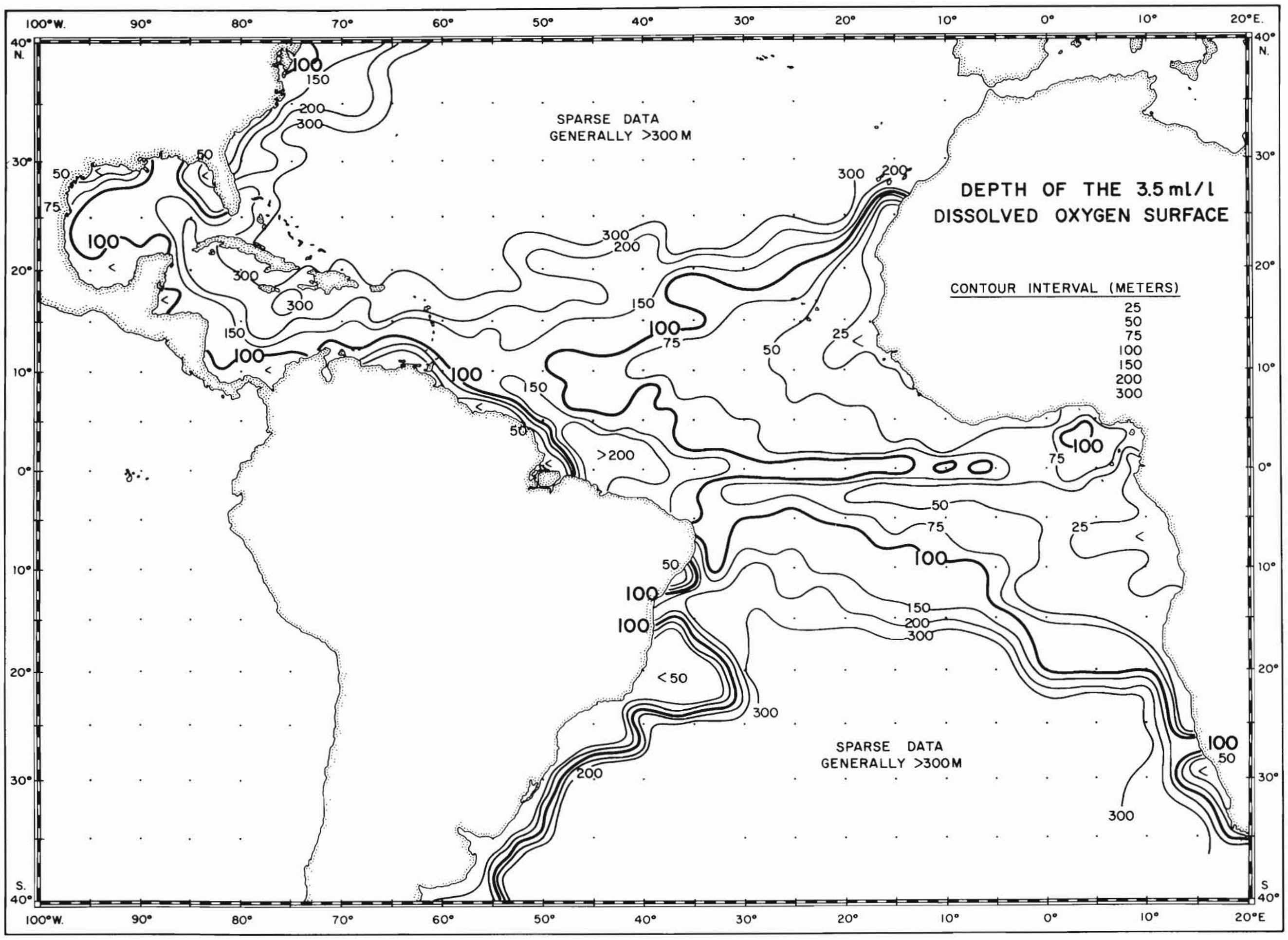

Figure 7.—Long-term annual mean depth of the 3.5 ml/l dissolved oxygen surface.

shore and equatorward in the area in question, thereby creating features in the 3.5 ml/l contours that are not consistent with or observed in the contours for the depth of the 18°C isotherm or sea surface temperature.

Figure 8 depicts the areal depth of skipjack tuna habitat indicating that skipjack tuna are capable of inhabiting almost all of the Atlantic between lat. 40°N and 34°S. Except for areas influenced by coastal upwelling, habitat depth is controlled by the depth of the 18°C surface poleward of about 15° latitude in either hemisphere. In the equatorial band (between lat. 15°N and 15°S), habitat depth is determined by dissolved oxygen concentration.

Having established that skipjack tuna can inhabit portions of the water column in most of the Atlantic between lat. 40°N and 34°S, it is necessary to define and limit those areas where skipjack tuna may be vulnerable to surface fishing gear. It seems reasonable that skipjack would be most vulnerable in those areas where their habitat is restricted to the near-surface layer. This is suggested by each of the panels in Figure 2. Figures 2A and 2B depict results of eastern tropical Pacific studies relating skipjack tuna purse seine success to the depth of the mixed (isothermal) layer. Both Figures 2A (Green, 1967) and 2B (Miller and Evans, footnote 1) utilize eastern tropical Pacific skipjack tuna purse seine data from the early 1960's and 1970's, respectively. Figure 2C (Ingham et al., 1977) compares Atlantic research ship sightings of surface skipjack tuna schools to oxycline depth.

Catch/school sighting trends with depth are remarkably similar in each panel. At depths shallower than the "critical depth" (defined as the mode of each of the distributions in Figure 2), catch and school sightings drop off markedly. At depths greater than the "critical depth," catch and school sightings drop off more slowly and in an exponential fashion as is indicated by the log

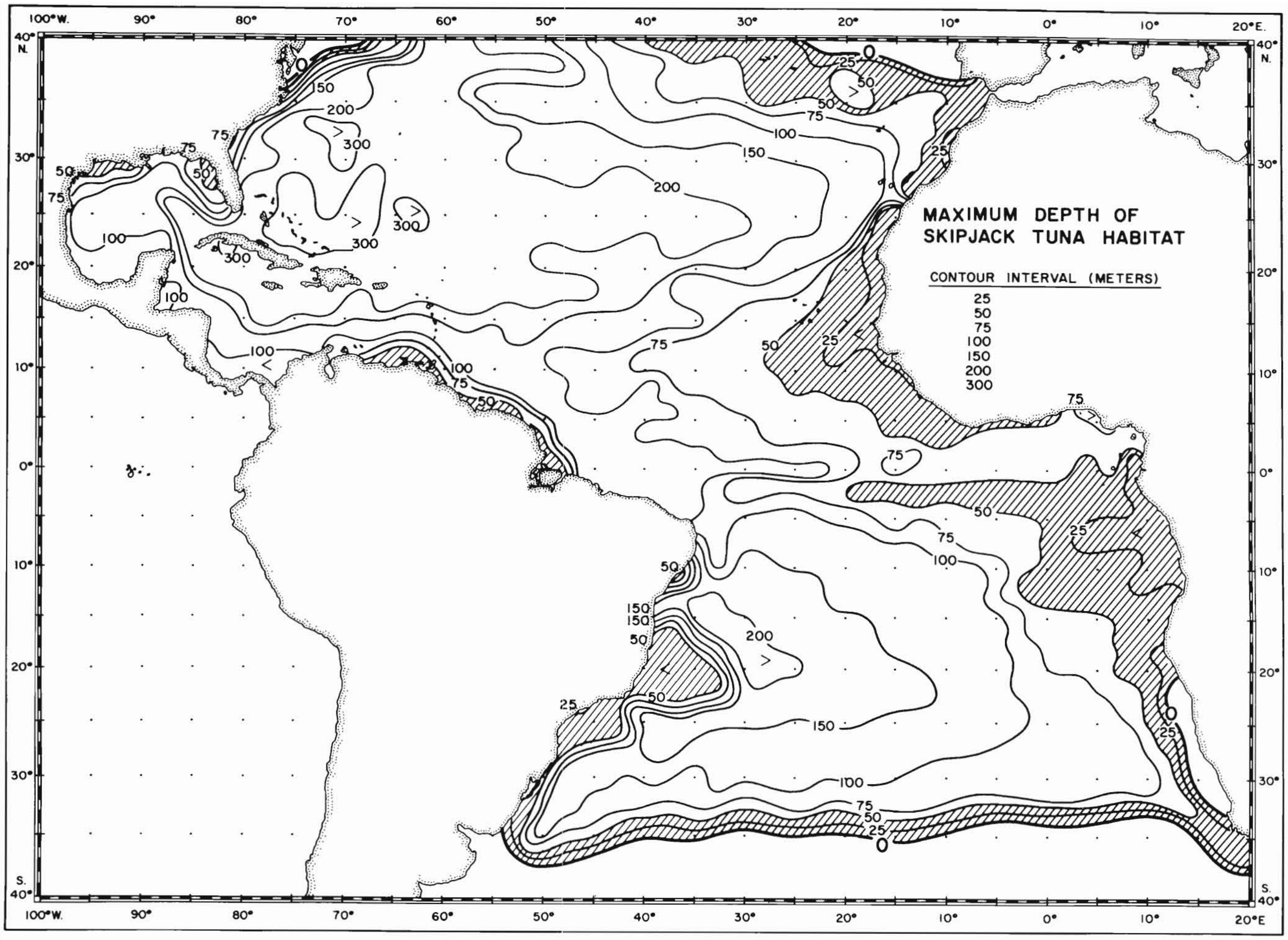

Figure 8.—Annual mean contours of maximum depth of skipjack tuna habitat, derived from graphical integration of Figures 6 and 7. Hatched areas indicate depths less than 50 m.

curve which has been fitted in each case. This suggests that skipjack tuna are less vulnerable in areas where the habitat depth is shallower than the critical depth (10-15 m). Decreased vulnerability in these shallow layers may be due to avoidance of such a constrained environment for possibly habitat layers shallower than 10-15 m do not routinely exist in nature. At habitat depths deeper than 10-15 m skipjack tuna catch/school sightings fall off more slowly. This decrease in vulnerability may be due to a simple increase in habitat volume.

For all three of the studies depicted in Figure 2, catch or school sightings are zero or extremely small for mixed layer or oxycline depths deeper than 50 m. It can be reasonably concluded, therefore, that skipjack tuna are not vulnerable to surface fishing gear or detection in areas where either of these parameters exceeds 50 m depth.

To examine this hypothesis, equivalence of oxycline and mixed layer depths to the 3.5 ml/l and 18°C surfaces, respectively, must be established. In this regard, the criteria used to define the oxycline in Figure 2C is the 3.5 ml/l surface (Ingham et al., 1977). Where the lower habitat limit is the 18°C isotherm it will by definition be equal to or deeper than the mixed layer depth. Therefore, the habitat depth will be either coincident with or somewhat deeper than the oxycline or mixed layer depth. Consequently, a habitat depth of 50 m would seem a reasonable assumed limit of vulnerability of skipjack tuna to surface gear.

To test the validity of a maximum depth of vulnerability, the 50 m habitat depth contour was plotted over the catch distribution for skipjack tuna for the FIS fleet for 1969-1977 (Fig. 4). Essentially all the catch falls in areas where the habitat depth is less than 50 m. A notable exception occurs in a nar-

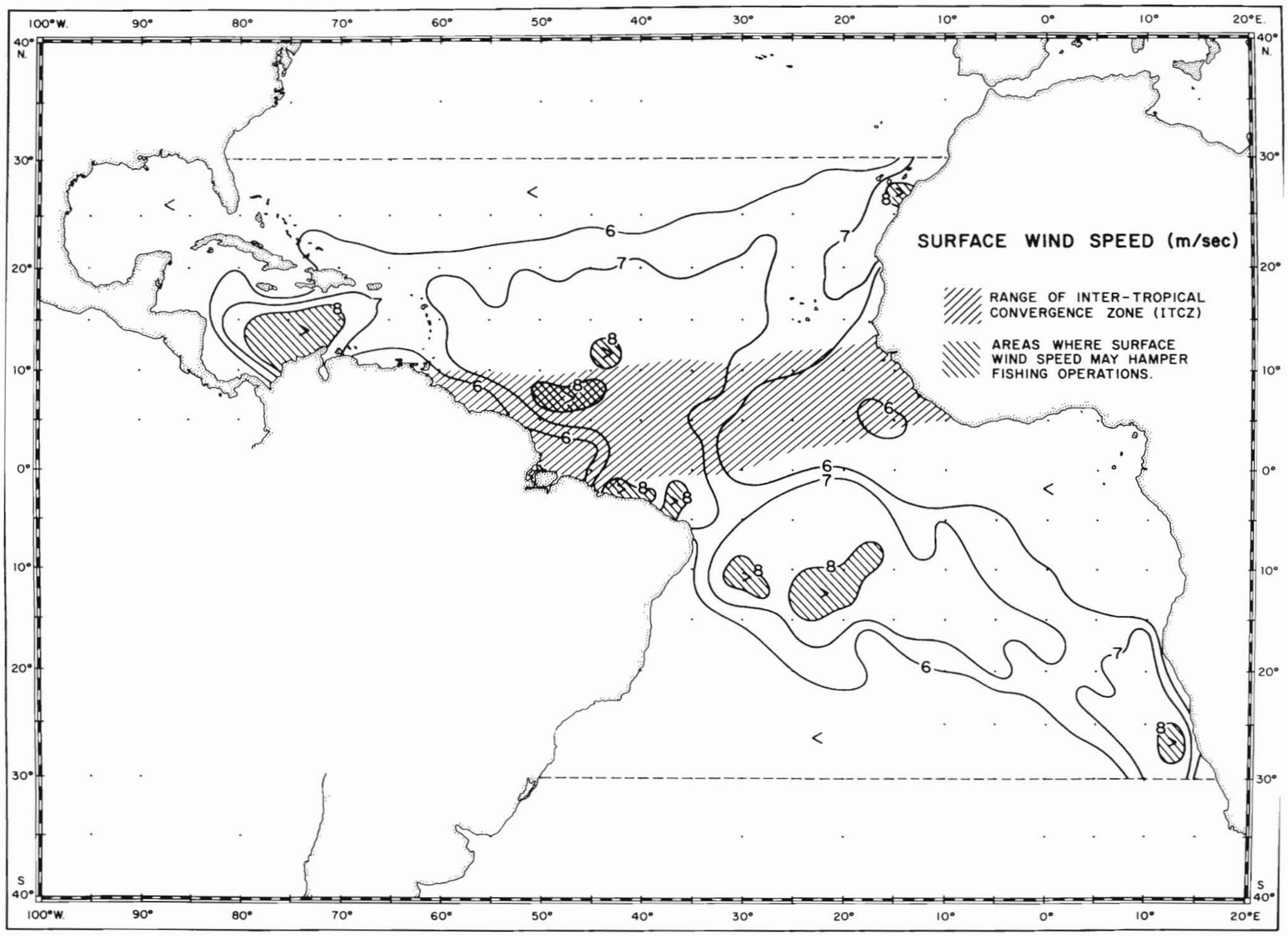

Figure 9.—Long-term mean annual contours of the seasonal range of selected sea surface wind speed values (m/second). Hatching depicts those areas where the surface wind speed is equal to or greater than 8 m/second and/or the annual range of the Inter-Tropical Convergence Zone; based on convergence of the surface wind field.

row band just north of the Equator between the coast and long. 6° W where the habitat is 50-75 m deep (Fig. 8). This is an area of highly variable oceanographic conditions (Dietrich, 1963). It is possible that the habitat depth in this area is less than 50 m on a seasonal basis and that the indicated catch occurs during these periods.

A maximum depth (50 m) of vulnerability of skipjack tuna to surface gear is indicated by hatching in Figure 8. As indicated, several areas in the western Atlantic have habitat depths appropriate for skipjack tuna vulnerability to surface gear (Fig. 8) including: 1) Off Argentina and along the south coast of Brazil, 2) off Venezuela and along the north coast of Brazil, 3) along the northern half of the Gulf Stream off the United States, and 4) along a band extending northwestward from the northwest African coast.

As previously indicated, surface wind speed can seriously restrict fishing operations and thereby the catchability of skipjack tuna by surface gear. Since purse seining success falls off markedly at wind speeds above 8 m/second (Fig. 3), that value has been taken as critical and areas where wind speed may exceed that value during the year have been hatched in Figure 9. Of those areas having high wind conditions only the area off Africa at lat. 28°S is coincident with an area where the skipjack tuna habitat depth is less than 50 m.

Figure 9 also includes the annual range of position of the Inter-Tropical Convergence Zone (ITCZ); that region where easterly trade winds from the northern and southern hemispheres meet. The ITCZ is traditionally an area of alternately squally, severe weather and light winds. Fishermen purse seining for tuna in the tropical

Pacific often fish in the area of light winds found on occasion adjacent to the ITCZ.

Conclusions

Previous research demonstrates that relationships between the behavior or catch of skipjack tuna and the marine environment can be defined. An analysis of this research indicates that the depth of the 3.5 ml/l dissolved oxygen surface and the depth of the 18°C isotherm in combination provide viable constraints on skipjack habitat. Applying these constraints to existing environmental data fields yields three-dimensional representations of skipjack tuna habitat which show that: 1) Almost all of the surface layer of the Atlantic Ocean between lat. 40°N and 34°S is suitable for habitation by skipjack; 2) the habitat depth or floor is shallowest in the eastern Atlantic, becoming deeper toward the west with the deepest areas occurring at the center of the subtropical gyres in either hemisphere; 3) coastal upwelling of nutrients feeds areas of high primary production which in turn cause shoaling of the oxygen maximum layer, the 3.5 ml/l surface and the habitat floor; and 4) advection and turbulent mixing may tend to displace areas of shoaling associated with primary production away from the upwelling source area.

Definition of skipjack tuna habitat does not imply they will be vulnerable to surface fishing gear throughout their range. Previous studies suggest that skipjack tuna cease to be vulnerable to surface gear at habitat depths in excess of 50 m. This concept is tested with favorable results against the catch by surface gear of the FIS fleet and then extrapolated to the western Atlantic to determine areas of high expected vulnerability.

The areas of high potential skipjack vulnerability in the western Atlantic include: 1) The nearshore regions off the east coasts of Brazil and Argentina between lat. 16°S and 32°S, 2) the areas off the north coast of Brazil and Venezuela between long. 48°W and 68°W, and 3) the northern edge of the Gulf Stream off the east coast of the United States north of lat. 35° N.

Finally, surface wind speed is shown to hamper fishing operations with purse seine gear when the wind speed exceeds 8 m/second. Those areas where the vector mean wind speed may exceed this value seasonally are outlined and are generally found to lie outside areas of potential skipjack vulnerability.

Future Research

At this point it is appropriate to indicate that the use of annual mean oceanographic data to define skipjack habitat has certain drawbacks. Averaging over extended scales in both time and space can have the effect of: 1) Masking seasonal and spatial fluctuations in the various data fields, 2) allowing extreme values in a locale (in both time and space) to dominate annual signals, and 3) causing areas of high variability in the data fields to appear constant in space and time.

As a result, the analyses presented herein may fail to depict or sometimes misrepresent skipjack tuna habitat over small areas or where only seasonal vulnerability occurs. A case in point is that area of the Caribbean just to the west of the Lesser Antilles where turbulence from flow through the island arc and over shoal areas during March and April causes skipjack tuna to be locally vulnerable to surface gear (Ingham and Mahnken, 1966).

This does not mean, however, that the approach of using annual averaged data is invalid. On the contrary, the analyses in this paper provide an overview of conditions for the entire Atlantic. As such, they contain useful information for resource exploitation and management and aids for determining those areas to which further research addressing shorter time scales should be directed.

Acknowledgments

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Note added in proof: This paper was first presented to the International Commission for the Conservation of Atlantic Tunas (ICCAT) in November 1979. In 1980 the catch of skipjack tuna by Brazil increased more than threefold to 7,000 t (ICCAT preliminary figures). All of the increased catch appears to have come from an area off southern Brazil defined by the authors as suitable skipjack habitat and an area where skipjack should be routinely vulnerable to surface fishing gear.

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