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Spatial and temporal distribution of purse-seine yellowfin tuna (*Thunnus albacares*) catches in relation to AVHRR-derived SST in the eastern tropical Pacific Ocean

Distribución espacial y temporal de las capturas con red de cerco de atún aleta amarilla (*Thunnus albacares*) en relación a la TSM derivada del sensor satelital AVHRR en el Océano Pacífico tropical oriental

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Abstract
Purse-seine yellowfin tuna (*Thunnus albacares*) catch and effort data and satellite monthly composite images of the Advanced Very High Resolution Radiometer (AVHRR) derived sea surface temperature (SST) were used to examine the relationship between the aggregation of yellowfin and the distribution of SST in the eastern tropical Pacific during the period 1995-2003. Monthly catch per unit effort (CPUE) values were calculated as the catch in metric tonnes/number of fishing days in a 1° latitude x 1° longitude grid and used as the relative abundance index. In total, 33,542 purse-seine yellowfin CPUE data were used. Results obtained allow establishing the SST range between 26ºC and 30ºC as the "preferred" thermal range for yellowfin tuna in the eastern tropical Pacific, and the SST range between 28ºC and 30ºC as the most favorable SST range of yellowfin fishing success. The consistent occurrence of yellowfin tuna in the relatively shallow mixed surface layer (≈40-50 m) of homogeneous temperature predominant in the eastern tropical Pacific suggests that the "preferred" SST range for yellowfin found in this study may be representative of the optimal thermal habitat of this species.

Keywords: ETP, Purse-seine fishery, Satellite oceanography, SST, Yellowfin tuna

Resumen
Datos de captura y esfuerzo de la pesquería cerquera de atún aleta amarilla (*Thunnus albacares*) e imágenes satelitales mensuales de la temperatura superficial del mar (TSM) obtenidas del sensor Radiómetro Avanzado de Muy Alta Resolución (AVHRR) fueron usadas para examinar la relación entre la agregación de atún aleta amarilla y la distribución de TSM en el Pacífico tropical oriental durante el período 1995-2003. Valores mensuales de captura por unidad de esfuerzo (CPUE) fueron calculados como la captura en toneladas métricas/el número de días de pesca en una cuadrícula de 1° de latitud x 1° de longitud y utilizados como el índice relativo de abundancia. En total, 33.542 datos de CPUE de aleta amarilla fueron utilizados. Los resultados obtenidos permiten establecer el rango de TSM entre 26ºC y 30ºC como el rango térmico "preferido" del atún aleta amarilla en el Pacífico tropical oriental, y el rango de TSM entre 28ºC y 30ºC como el rango de temperatura más favorable para la pesca exitosa de aleta amarilla. La consistente ocurrencia de atún aleta amarilla en la relativamente delgada capa de mezcla superficial (≈40-50 m) de temperatura homogénea predominante en el Pacífico tropical oriental sugiere que el rango de TSM "preferido" del atún aleta amarilla encontrado en este estudio puede ser representativo del hábitat térmico óptimo de esta especie.

Palabras claves: Aleta amarilla, Oceanografía satelital, OPO, Pesquería cerquera,TSM

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Introduction

Joint analysis of biological/catch and concurrent satellite sensed environmental data time series can be used to determine relationships between the environment and the behavior, distribution and abundance of high economic value fish stocks, helping fisheries managers to regulate maximum catches in order to ensure the sustainability of the fishing resources into the future.

Despite the complexity of the interactions between the fish and its environment, it is important for solving fisheries problems to try to relate directly environmental factors with the distribution and abundance of fishing resources, and often the practical approach to do this is to investigate first the variability of individual environmental factors and their associated biological responses (Laevastu and Hayes, 1981; Santos, 2000). One of these environmental factors is the water temperature which is both directly and, through various ways, indirectly, the truly significant environmental factor. In most cases, the temperature may serve as a most useful indicator of the prevailing and changing ecological conditions, and of important ocean processes such as advection, upwelling and mesoscale dynamic features such as fronts, meanders and eddies (Laevastu and Hayes, 1981).

Fish have the ability to perceive and select a limited thermal range in which they tend to congregate; this is generally the thermal range which offers them the opportunity for maximum expression of activity and is ultimately evident in their abundance and distribution (Laevastu and Hayes, 1981). Fishermen have long made use of this usually observed association of fish with thermal ranges, relying frequently on sea surface temperature (SST) to set the gear in places of fish aggregation (Santos, 2000).

The satellite measured SST provides both a synoptic view of the ocean and a high frequency of repeat views, allowing the examination of basin-wide upper ocean dynamics not possible by other means, e.g. ships or buoys. Since the 1980s satellites have been increasingly utilized to measure SST and have provided an enormous leap in our ability to view the spatial and temporal variation in SST. Thus, satellite SST data can help to improve the efficiency of fishing efforts and, simultaneously, the management of fishing resources by identifying those thermal features that are often places of fish aggregation (Santos, 2000).

In that respect, several investigators have attempted to associate the distribution and availability of tunas with satellite-derived SST and thermal structures, with varying degree of success. Laurs *et al.* (1984) showed evidence of the relationship between the distribution and availability of albacore tuna (*Thunnus alalunga*) and oceanic and near-shore fronts off the US west coast. Fiedler and Bernard (1987) demonstrated that the distribution and diet of albacore and skipjack (*Katsuwonus pelamis*) tunas caught off California were related to mesoscale frontal structures. Power and May (1991) found no discernible relationship between SST and their gradients and yellowfin tuna (*Thunnus albacares*) nominal catch-per-unit-effort (CPUE) in the Gulf of Mexico. Kumari *et al.* (1993) established a relationship between yellowfin CPUE and SST in Indian waters, showing that highest CPUE corresponded to areas where SST ranged between 27ºC and 29ºC. Andrade and García (1999) reported that highest skipjack CPUE off southern Brazil corresponded to areas with SST between 22ºC and 26.5ºC. Zagaglia *et al.* (2004) showed that SST influences but it does not seem to be the main determinant of the area distribution and the relative abundance of yellowfin tuna in the equatorial Atlantic. Liu *et al.* (2004) reported that bigeye tuna (*Thunnus obesus*) CPUE was higher in regions where SST ranged between 26ºC and 28ºC in the eastern tropical Pacific Ocean. Santos *et al.* (2006) did not find a "preferred" SST range for albacore and bigeye tunas off the west coast of Portugal. Zainuddin *et al.* (2008) showed that highest albacore CPUE were associated with SST between 18.5ºC and 21.5ºC in the western North Pacific. Mugo *et al.* (2010) found that SST was the best habitat predictor for skipjack tuna in the western North Pacific. Lan *et al.* (2012) showed that monthly variations in yellowfin CPUE were significantly correlated with SST in the Arabian Sea.

Although most studies dealing with the association between tuna and satellite-sensed SST and thermal features in different regions of the world's oceans have been directed to the longline tuna fisheries, no one concerning the relationship between yellowfin tuna aggregation and satellite-derived SST has been conducted at the scale of the eastern tropical Pacific using the purse-seine fishery data. Thus, the aim of the present study is to examine the relationship between the aggregation of yellowfin tuna (*Thunnus albacares*) in the eastern tropical Pacific as inferred from purse-seine catch data, expressed as CPUE, and the distribution of satellite-derived SST.

The yellowfin tuna fishery in the eastern tropical Pacific

The eastern tropical Pacific Ocean supports one of the most valuable tuna fisheries in the world which, on average, yields more than 600,000 metric tonnes (t) annually and is exploited by an international purse-seine fishing fleet that comprises vessels from more than 10 countries. The largest fleets are the Ecuadorian and Mexican fleets, representing half of the total well volume (IATTC, 2015). Five are the major commercial species of tunas in the eastern tropical Pacific: albacore (*Thunnus alalunga*), bigeye (*Thunnus obesus*), bluefin (*Thunnus thynnus*), skipjack (*Katsuwonus pelamis*) and yellowfin (*Thunnus albacares*).

The yellowfin fishery in the eastern tropical Pacific is one of the most important in the world. During the study period, the annual catch, by all types of gear combined, increased from 244,639 t in 1995 to 416,018 t in 2003, and averaged 327,304 t, or about 27% of the world production (IATTC, 2015).

Yellowfin tuna is an epipelagic oceanic species found worldwide in tropical oceanic regions. In the Pacific Ocean, yellowfin are distributed across the entire tropical region, but the bulk of the catch is made to the east and to the west (IATTC, 2015). In the eastern tropical Pacific, the average distribution of purse-seine catches of yellowfin tuna ranges between 30ºN and 20ºS and from the coast of Central and South America to about 150ºW (figure 1).

The eastern tropical Pacific purse-seine tuna fishery catches yellowfin tuna all year round, accounting for about 50% of the total tuna catch (IATTC, 2015). The purse-seine is by far the most effective technique for capturing yellowfin tuna in the eastern tropical Pacific, taking more than 90% of the total catch. Purse-seining for tuna in the eastern tropical Pacific can be conducted in three ways: the net may be set around schools of tuna associated with dolphins [dolphin sets], around schools of tuna associated with logs or other floating objects [floating objects sets], or around unassociated schools of tuna [school sets] (IATTC, 2015).

Materials and methods

Fishery data

The fishing data used in this study were provided by the IATTC whose personnel collect landings data, abstract the logbooks of tuna vessels to obtain catch and effort data, measure fish and collect other biological data, and assist with the training, placement, and debriefing of observers aboard tuna vessels operating in the eastern tropical Pacific (IATTC, 2015).

Monthly yellowfin tuna catch (metric tonnes) and effort (fishing days) data set arranged by 1° latitude x 1° longitude areas were obtained from the IATTC. From this data set, the nominal CPUE was derived and used as the relative abundance index. Monthly CPUE values were calculated as the sum of all catches in metric tonnes/the sum of all fishing days for each month in a 1° latitude x 1° longitude grid. The data set encompasses the period from 1995 to 2003, except 1997 and 1998. Data from the 1997 and 1998 years were not used in this study due to the large ocean and atmosphere anomalies resulting from the strong El Niño event occurred in those years which may have affected in a very peculiar way the distribution of yellowfin tuna in the study region. For instance, during the mature phase of El Niño, the thermal structure is significantly

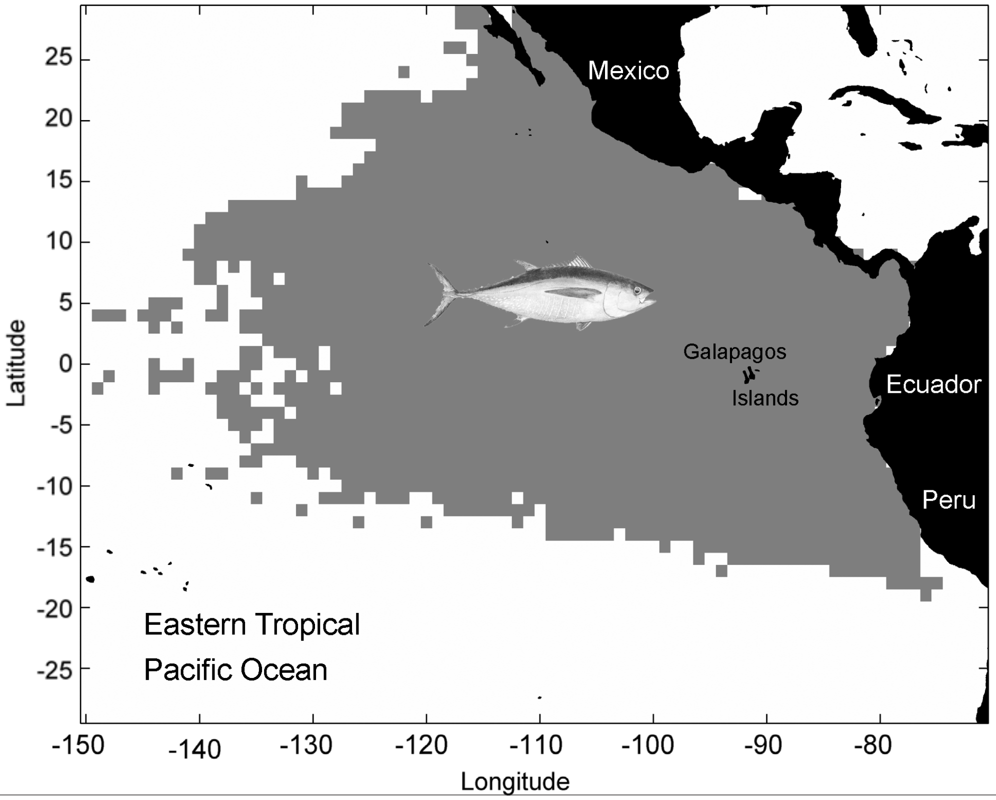

Figure 1. Spatial range of the yellowfin (*Thunnus albacares*) catches (gray area) in the purse-seine tuna fishery of the eastern tropical Pacific Ocean (period 1995-2003).

depressed in the eastern tropical Pacific, being evident a remarkable deepening of the thermocline (Philander, 1989; Ruiz *et al.*, 2005; Wang *et al.*, 2017). A deeper thermocline extends the vertical habitat of yellowfin, reducing the concentration of this species in shallower water and its vulnerability to surface fishing gear. Thus, catches of yellowfin tuna may have been greatly affected by the deeper thermocline during El Niño (IATTC, 2015). Here, the aim is to examine the relationship between the aggregation of yellowfin tuna in the eastern tropical Pacific and the distribution of satellite-derived SST during 'normal' conditions, which for the purpose of this work may be defined as non-El Niño conditions.

During the study period some measures for the conservation of yellowfin tuna in the eastern tropical Pacific were in effect, based on recommendations of the IATTC scientific staff (Cucalón-Zenck, 2005). From 1999 to 2001, a total allowable catch (TAC) system was adopted for the purse-seine yellowfin tuna fishery; when the annual limit was reached, purse-seining for yellowfin ceased. This measure affected mainly the yellowfin catches during the last month of the year. Also, closure periods were adopted for the purse-seine tuna fishery in December 2002 and December 2003; the first period covered the entire eastern tropical Pacific region and the second some specific areas. Overall, these measures would affect the estimation of the yellowfin fishing effort, and hence of the CPUE, since fishing for other tuna species remained open. Consequently, fishing data corresponding to December of years 1999 to 2003 were not used in the present study. In total, 33,542 purse-seine yellowfin CPUE data were available for this work.

In the eastern tropical Pacific, yellowfin tuna are caught in three types of purse-seine sets: dolphin sets, floating objects sets and school sets. In the present study, no distinction was made between set types, and the yellowfin catch was computed as the sum of catches of the different sets.

Temporal variability of yellowfin tuna CPUE

Monthly CPUE values were calculated as the sum of all catches divided by the sum of all days of fishing for each month of the study period. From these data, yearly and monthly means were computed to examine the annual and seasonal variability of the yellowfin tuna catch rates, respectively. Unless otherwise stated, seasons are referred to the northern hemisphere throughout this work.

Satellite data

SST data derived from the Advanced Very High Resolution Radiometer (AVHRR) sensor on board the National Oceanic and Atmospheric Administration (NOAA) satellites are produced and distributed by the Physical Oceanography Distributed Active Archive Center (PO.DAAC) of the Jet Propulsion Laboratory (JPL)/National Aeronautics and Space Administration (NASA). There are eight possible quality levels (levels 0 to 7) to which a pixel may be assigned depending on what series of statistical tests are passed (0 indicates very bad SST data). The best SST data only contains pixels of quality 4 or better, with cloud-associated areas and far portions of the swath rejected (Kilpatrick *et al.*, 2001). In the present study, monthly averages of the AVHRR derived L3 nighttime SST data, containing pixels of quality level 4, were obtained from PO.DAAC (http://podaac.jpl.nasa.gov) to produce monthly composite images for the eastern tropical Pacific for the same period as the fishing data.

Since the spatial resolution of the AVHRR Pathfinder V5 SST data is 4.88 km, the SST images were resampled onto a 1° latitude x 1° longitude grid to match the fishing data. However, SST images at original resolution were used for display purposes in some figures.

Cloud cover reduced the number of satellite SST data in each image with a clearly defined spatial and seasonal pattern of the coverage associated with the most northerly position of the InterTropical Convergence Zone (ITCZ) from June to November. This, in turn, reduced the number of CPUE data used for combined SST-CPUE analysis. Overall, nearly 22% of the total available CPUE data did not go into analysis because of missing SST counterparts due to cloud-cover conditions during the study period.

Yellowfin tuna CPUE and SST relationship

The possible relationship among the surface thermal field and purse-seine yellowfin tuna fishing success was examined by computing summary statistics between the SST and CPUE data.

The yellowfin tuna CPUE data was strongly asymmetric and Lilliefors' composite goodness-of-fit test confirmed that the data were not normally distributed at the 5% significance level, even after logarithmic transformation log (CPUE+1) was applied to lessen the effect of extreme values. Therefore, the median was used as a measure of data central tendency in the subsequent analysis.

The CPUE data were first sorted out by SST classes and the CPUE median of each class was computed. Based on the distribution of CPUE medians by SST classes, the entire CPUE data set was then classified under two different groups according to the magnitude of the SST (<28°C and ≥ 28°C), and the CPUE median of each group was computed. A non-parametric statistical test (Mann-Whitney *U*-test) was applied to verify the statistical significance of the difference among the CPUE medians.

For all purposes throughout this study, zero CPUE values mean that there was fishing effort but there was no catch.

Results

Temporal variability of yellowfin tuna CPUE

Figure 2 presents the yearly yellowfin tuna catch and averaged CPUE obtained by the purse-seine tuna fishing

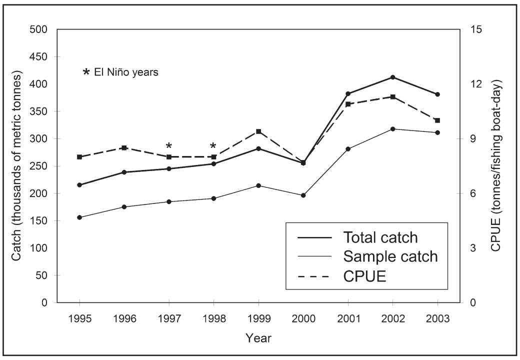

Figure 2. Yearly yellowfin tuna (*Thunnus albacares*) catch and averaged CPUE in the eastern tropical Pacific Ocean during the study period. The sample catch (thin line) and CPUE (dashed line) are computed from the sample data used in this work, while the total catch (thick line) is collected from landings data.

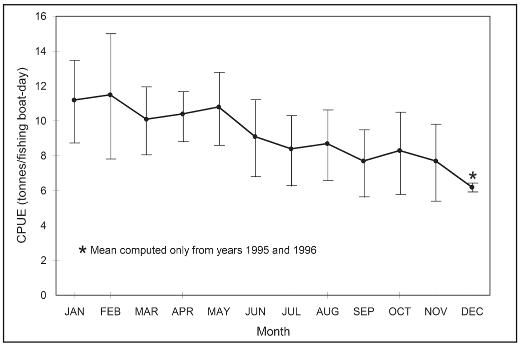

Figure 3. Temporal variability of yellowfin tuna (*Thunnus albacares*) CPUE in the eastern tropical Pacific Ocean for the study period. Vertical bars indicate one standard deviation.

fleet in the eastern tropical Pacific during the study period. It is evident a synchronous variation between the sample catch, as obtained from the sample data used in this work, and the total catch collected from landings data; the former representing between 72% and 82% of the total catch. In addition, an increasing ‘trend’ of yellowfin tuna catch and CPUE is clear, being also evident a synchronous variation between these two distributions from 1995 to 2003, excluding the 1997 and 1998 El Niño years. Both catch and CPUE showed a smooth increase from 1995 to 1999 and a slight decrease in 2000. Thereafter, a remarkable increase was observed in both distributions. In fact, the purse-seine catch of yellowfin tuna in 2002, 412,000 t, was the greatest on record. Overall, it may be said that the yellowfin tuna fishery of the eastern tropical Pacific was going through a relatively healthy phase during the study period.

Yellowfin CPUE show seasonal variability, with higher values occurring from January to May and minimum values from September to December (figure 3). The conspicuous low value of the CPUE mean in December is possibly related to the fact that, for the reasons mentioned above, it was computed from only the 1995 and 1996 years when catch rates were considerably lower than in the subsequent years.

Spatial distribution of yellowfin tuna CPUE

The mean spatial distributions of the purse-seine yellowfin tuna CPUE in the eastern tropical Pacific for the first and third quarters, which are representative of winter and summer conditions, respectively, are presented in figure 4. The remaining seasons may be considered as transition periods between these two. Overall, these distributions show a clearly defined spatial and seasonal pattern in yellowfin catch rates.

In winter, two major areas of high aggregations of yellowfin tuna are evidenced on different sides of the equator: one area extends from 83ºW to about 117ºW between approximately 5ºN and 20ºN, excluding a zonal band stretching from the coast of Central America to 104ºW between 10ºN and 14ºN where catches are notably lower; and the other area, less prominent than the former, runs between the equator and 4ºS from 120ºW to approximately 90ºW where it turns southeastward following a direction almost parallel to the South American coast to reach 16ºS between 80ºW and 85ºW (figure 4a).

In summer, one major area of high aggregations of yellowfin tuna is evident, which extends from near the coast of Central America to approximately 140ºW between 7ºN and about 20ºN (figure 4b). At this time, fishing operations retreat northward close to the South American coast, and expand westward with respect to the winter situation.

Catches in relation to sea surface temperature

In order to investigate the association of the purse-seine yellowfin fishing success with the surface thermal field, a quantitative analysis was performed using the CPUE data set and the contemporary satellite-derived SST images.

During the 7 years study period, yellowfin tuna were caught in the SST range 17ºC-31ºC, almost the entire range of SST measured in the study region. However, 80% of the total catch was obtained with SST values between 26ºC and 30ºC, and 52% between 27ºC and 28ºC (figure 5a).

On the other hand, the distribution of CPUE medians by SST classes revealed a broad mode between 28ºC and 30ºC. Thus, two major groups are evident: one group corresponding to SSTs higher or equal to 28ºC associated with maximum CPUE median values, and the other group corresponding to SSTs lower than 28ºC associated with minimum CPUE median values (figure 5b).

Based on the above results, the complete yellowfin tuna CPUE data set was then classified under the two SST groups, and the CPUE median of each group was computed. Table 1 presents the outcome of the non-parametric statistical test used to investigate if there is a significant difference between the CPUE medians. It shows that the highest yellowfin CPUE median is obtained in association with SSTs greater or equal to 28ºC, and that the difference between the CPUE medians is statistically very highly significant ($P<0.001$).

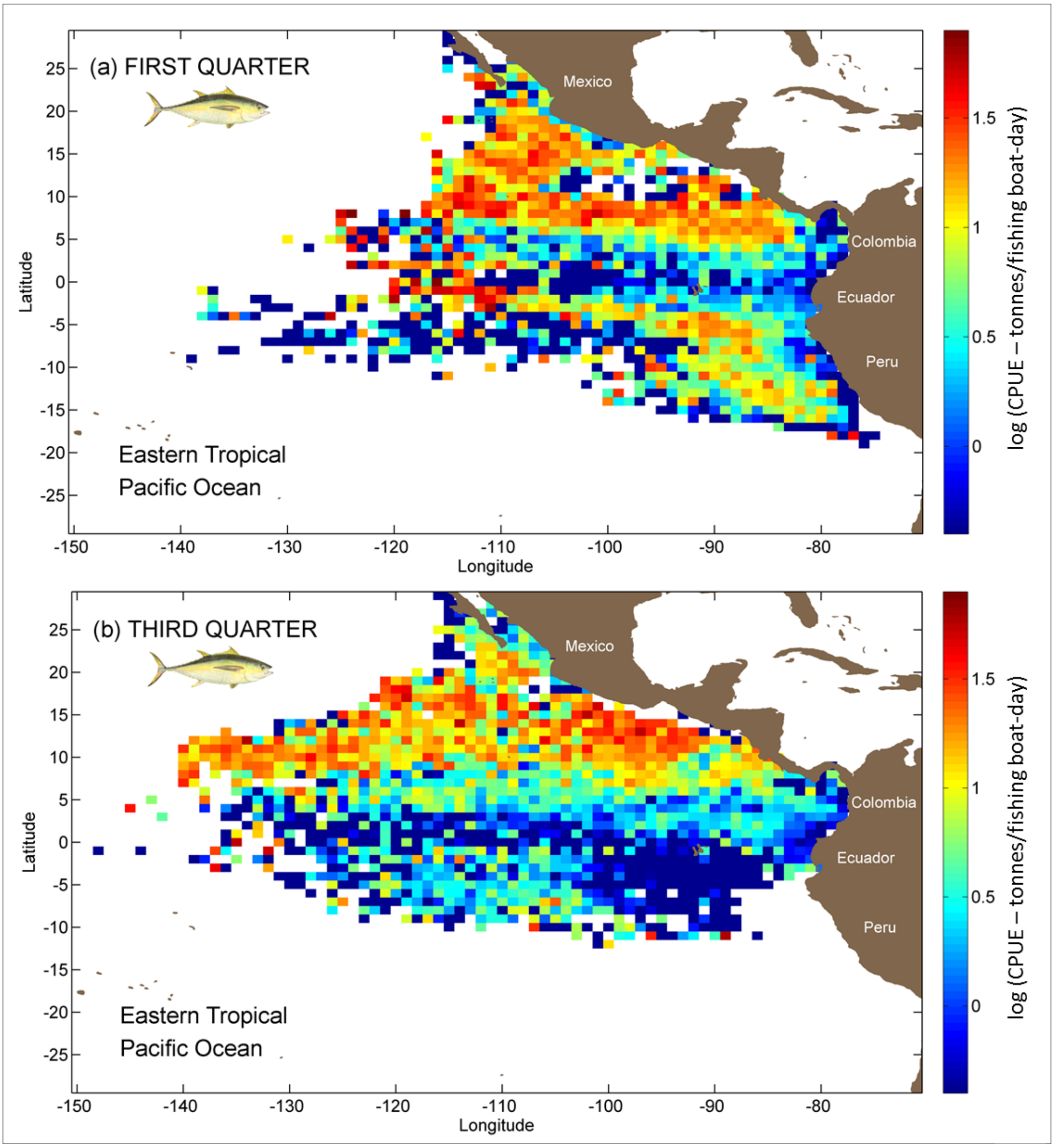

Figure 4. Mean spatial distribution of purse-seine yellowfin tuna (*Thunnus albacares*) CPUE in the eastern tropical Pacific Ocean for the (a) first and (b) third quarters of the year, period 1995 to 2003, except 1997 and 1998. CPUE values are presented on a logarithmic scale.

Seasonal variations in catches in relation to sea surface temperature

Seasonal variations were examined by computing the distribution of CPUE medians by SST classes for the first and third quarters, which are representative of winter and summer conditions, respectively (figures 6a and 7a). Overall, these distributions also show a broad mode between 28ºC and 30ºC. Thus, two major groups were formed in each case: one group corresponding to SSTs higher or equal to 28ºC and the other group corresponding to SSTs lower than 28ºC, and the CPUE median of each group was computed. Results of the statistical test are presented in Table 2 for the first and third quarters. They show that, in both seasons, the highest yellowfin CPUE median is obtained in association with SSTs greater or equal to 28ºC, and that the difference between the CPUE medians is statistically very highly significant.

The yellowfin abundance distribution relative to the available habitat, indicated by the SST frequency distribution, is shown in figures 6 and 7 for the first and third quarters, respectively. In both cases, the CPUE distribution is very different than the SST frequency distribution, showing that only 21% of total SSTs were in the range between 28ºC and 30ºC in the first quarter, and only 30% of total SSTs were in the range between 28ºC and 30ºC in the third quarter.

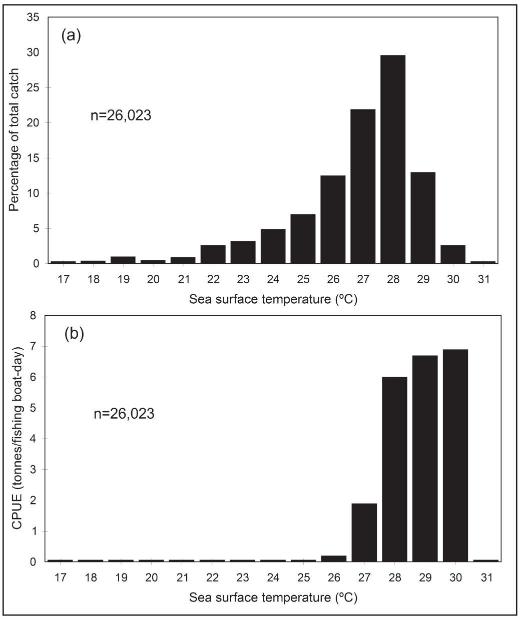

Figure 5. Distribution of purse-seine yellowfin tuna (*Thunnus albacares*) catch (a) and CPUE medians (b) by SST classes in the eastern tropical Pacific Ocean during the study period.

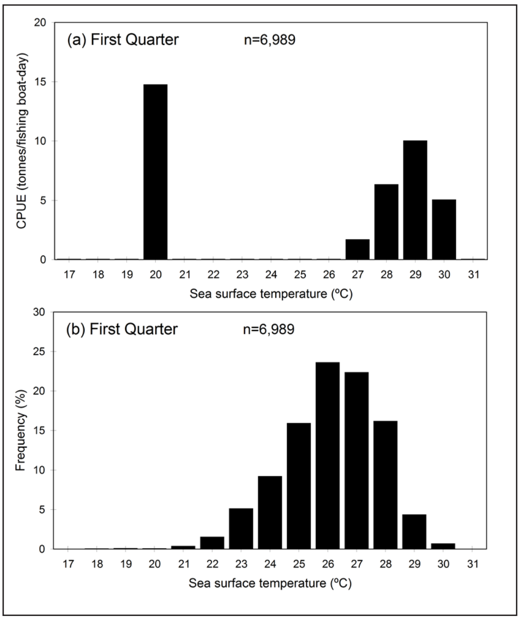

Figure 6. (a) Distribution of purse-seine yellowfin tuna (*Thunnus albacares*) CPUE medians by SST classes and (b) SST frequency distribution in the eastern tropical Pacific Ocean for the first quarter of the year.

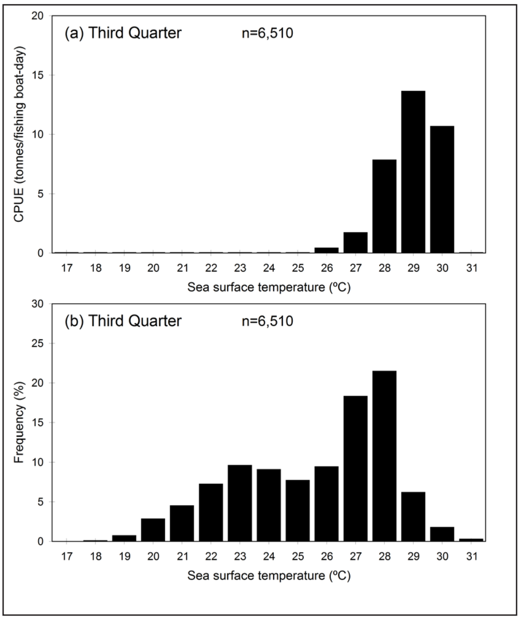

Figure 7. (a) Distribution of purse-seine yellowfin tuna (*Thunnus albacares*) CPUE medians by SST classes and (b) SST frequency distribution in the eastern tropical Pacific Ocean for the third quarter of the year.

Table 1. Summary of Mann-Whitney U statistics to test the significance of the difference between the median values of yellowfin tuna CPUE in relation with SST.

SST group	*N*	CPUE median	Probability
SST<28ºC	19,144	0	***
SST≥28ºC	6,879	6.17	

*** very highly significant (*P*<0.001)

Table 2. Summary of Mann-Whitney U statistics to test the significance of the difference between the median values of yellowfin tuna CPUE in relation with SST.

SST group	*N*	CPUE median	Probability
		FIRST QUARTER	
SST<28ºC	5,502	0	***
SST≥28ºC	1,490	7.24	
		THIRD QUARTER	
SST<28ºC	4,560	0	***
SST≥28ºC	1,950	8.79	

*** very highly significant (*P*<0.001)

The above relationships were further examined by a visual analysis of the entire sequence of SST satellite images with concurrent purse-seine yellowfin CPUE data used in the present study. In figures 8 and 9 are presented some typical examples of a situation that was repeatedly observed during this analysis. It is shown that, no matter the time of the year, most of the yellowfin catches were obtained in waters where SST was higher or equal to 26ºC, and most of the high CPUE values were found in waters where SST was higher or equal to 28ºC.

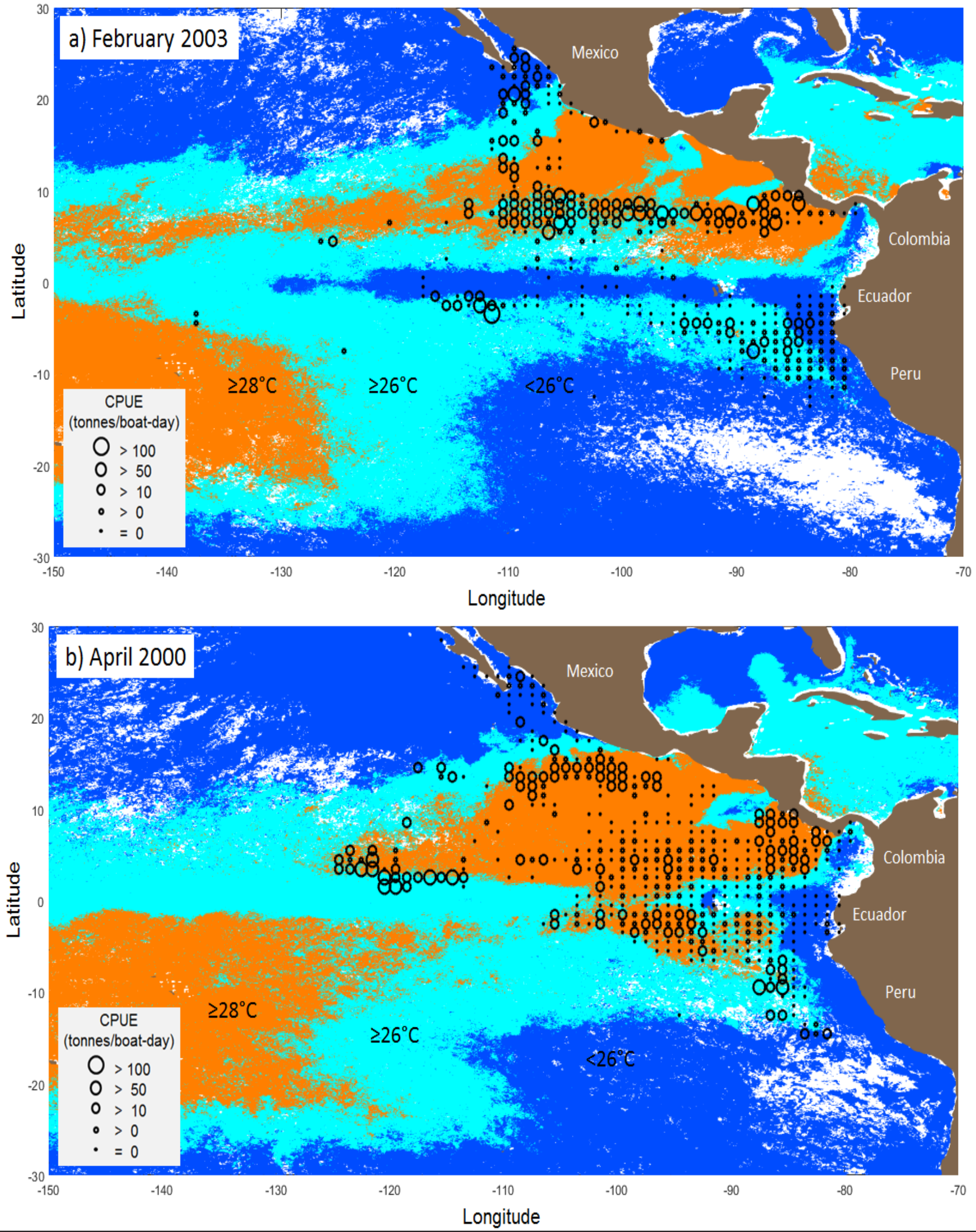

Figure 8. The spatial distribution of purse-seine yellowfin tuna (*Thunnus albacares*) CPUE in the eastern tropical Pacific Ocean in (a) February 2003 and (b) April 2000 overlain on AVHRR-derived SST images. Blue is SST lower than 26°C, Cyan is SST equal or higher than 26°C and Orange is SST equal or higher than 28°C, white is clouds and brown is land.

Discussion

Yellowfin tuna are distributed worldwide in all warm seas except the Mediterranean (Wild, 1994). In the Pacific Ocean, the yellowfin range of distribution has been generally reported to stretch from 40°N to 40°S latitude, with the northward spread of the species being slightly more pronounced in the western than in the eastern Pacific (Bardach, 1983; Sakagawa, 1996). In this study, it was established that the range of the purse-seine yellowfin tuna fishery in the eastern Pacific extends between 30°N and 20°S from the coast of Central and South America to approximately 150°W, although catches are lower close to the western boundary (figure 1).

Temperature has been found to be an important determinant of the distribution of yellowfin tuna. In the tropical Atlantic Ocean catches of yellowfin have been reported to occur in waters with SST limits between 22°C and 29°C (Stretta and Slepoukha, 1986), and preferentially above 25°C (Stretta, 1991); whereas in the equatorial Atlantic the largest catches of yellowfin have been observed to occur mostly in warm waters with SST above 27°C (Zagaglia *et al.*, 2004). In the Indian Ocean yellowfin tuna are mostly found in waters with SST above 25°C (Lee *et al.*, 1999), and the highest CPUE values have been reported to occur in areas with SST between 27°C and 29°C (Kumari *et al.*, 1993) and between 28°C and 30°C (Rajapaksha *et al.*, 2013).

Results from the present work allow establishing the SST range between 26°C and 30°C as the "preferred" thermal range for yellowfin tuna in the eastern tropical Pacific, and the SST range between 28°C and 30°C as the most favorable SST range of yellowfin fishing success (figure 5). No seasonal variations in catches in relation to SST were observed, as the above SST range of highest yellowfin CPUE remains the same in both winter and summer. The yellowfin abundance distribution relative to the available habitat, indicated by the SST frequency distribution, gives further support to the above temperature preferences, showing that only a small fraction (less than a third) of total SSTs were in the range between 28°C and 30°C in both seasons (figures 6 and 7).

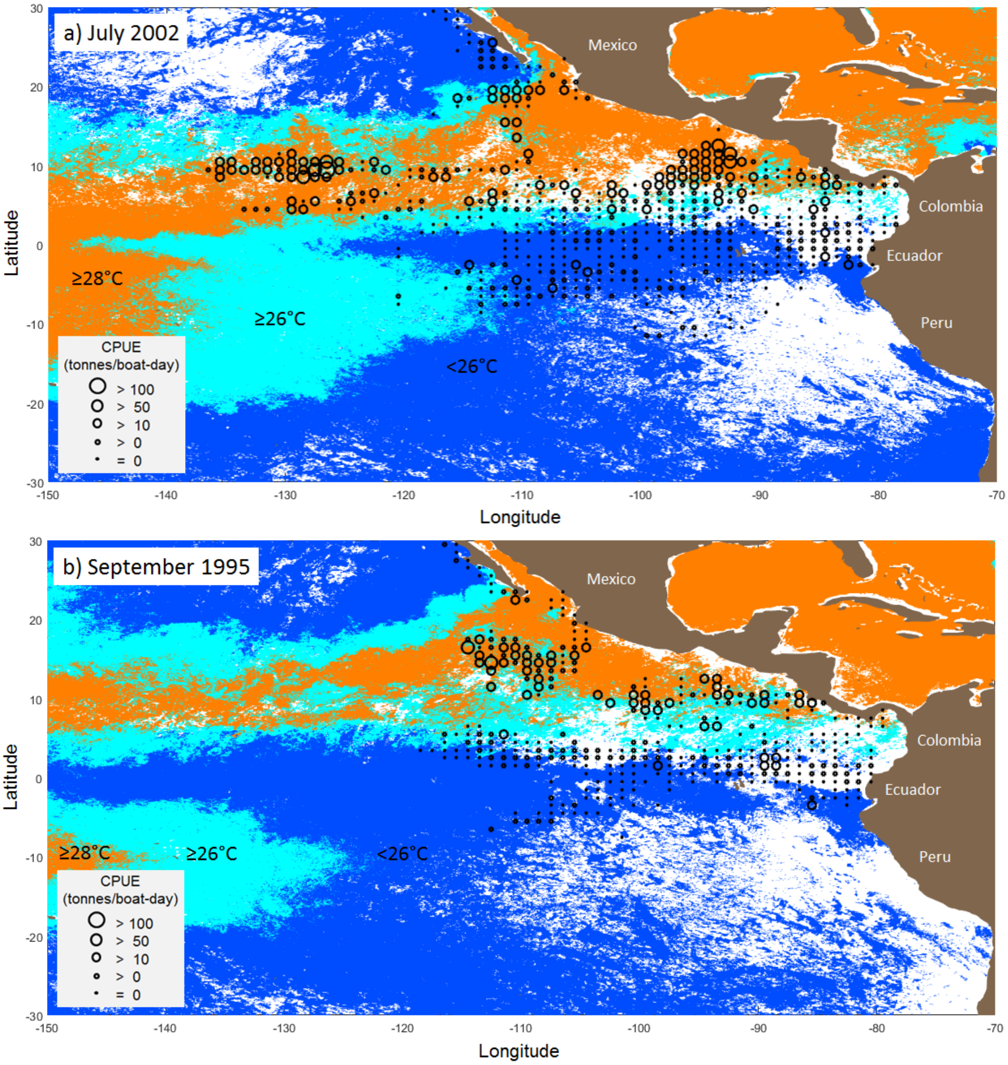

Figure 9. The spatial distribution of purse-seine yellowfin tuna (*Thunnus albacares*) CPUE in the eastern tropical Pacific Ocean in (a) July 2002 and (b) September 1995 overlain on AVHRR-derived SST images. Blue is SST lower than 26°C, Cyan is SST equal or higher than 26°C and Orange is SST equal or higher than 28°C, white is clouds and brown is land.

Overall, the present results agree well with those from previous studies in tropical waters, particularly with the reported SST range (28º-30ºC) of highest yellowfin CPUE in the Indian Ocean (Rajapaksha *et al*., 2013).

SST is one of the most important physical factors affecting the biology, dynamics and availability of tuna stocks because it modifies their geographical and vertical aggregation patterns through its effect on feeding, reproductive and migratory behavior, and body thermoregulation (Fonteneau, 1998). Acoustic telemetry studies of the small-scale movement patterns of yellowfin tuna in the eastern tropical Pacific and central Pacific have shown that this species spends most of their time in the warm-water mixed surface layer and above the thermocline, moving occasionally into colder waters below the thermocline for short periods (Carey and Olson, 1982; Holland *et al*., 1990; Block *et al*., 1997; Bard *et al*., 1998; Brill *et al*., 1999). In this regard, Dell *et al*. (2011) found that pelagic regions in the South Pacific Ocean with a shallow surface mixed layer are associated with high yellowfin tuna catch.

In the eastern tropical Pacific the structure of the near-surface water column is unusual because the stratification characteristic of tropical oceans is extreme in this region: the thermocline is shallow and strong (Lavín *et al*., 2006). The mean thermocline depth (depth of maximum vertical temperature gradient) between 5ºS and 15ºN east of 140ºW is predominantly less than 80 m, and the mixed layer depth (isothermal layer depth) is 20-50 m shallower than the thermocline (Fiedler and Talley, 2006). Thus, the consistent occurrence of yellowfin tuna in this relatively shallow layer of homogeneous temperature allows us to assume that the "preferred" SST range for yellowfin in the eastern tropical Pacific found in this study may be representative of the optimal thermal habitat of this species.

Also, this study allows establishing 20ºN and 5ºN as the northern and southern limits, respectively, for a larger concentration of yellowfin tuna throughout the year (figure 4). South of the equator, a secondary seasonal area of larger aggregation of yellowfin tuna occurring in winter is limited by 4ºS and about 16ºS between 80ºW and 90ºW (figure 4a). In this area, the aggregation of yellowfin tuna seems to be coupled with the seasonal displacements of the Peru Current. Thus, in winter, the larger concentration of this species is associated with the weakening and southward retreating of the Peru Current which is compensated by an advection of warm water (>25ºC) in the same direction. On the other hand, in summer, SSTs in this area become colder (<24ºC) as the Peru Current strengthens and reaches its most northern position near 5ºS where it turns northwestward to join the South Equatorial Current in the Galapagos Islands. Thus, the meridional displacement of the surface thermal field appears to be the factor that "pushes" the yellowfin tuna schools to this area during winter.

Conclusions

A discernible relationship between the aggregation of yellowfin tuna and the distribution of satellite-derived SST is revealed, allowing the establishment of thermal ranges for distribution and fishing of yellowfin in the eastern tropical Pacific. To the author's knowledge, it is the first time that such a relationship between yellowfin fishing success and SST distribution is observed in the eastern tropical Pacific using concurrent purse-seine tuna fishery and satellite-derived environmental data at these temporal and spatial scales. Overall, the seasonal distribution of yellowfin in the region seems to be coupled with seasonal variations of the surface thermal field mostly associated with advection processes. However, the observed relationship is not expected to be explained by temperature alone, but involve also other behavioral mechanisms probably related with feeding activity. Further studies need to be done to clarify the latter.

Recommendations

The results obtained in this study should encourage continuous efforts to explore and quantify the relationships between environmental factors and the distribution, aggregation and vulnerability of large and highly mobile pelagic fish, like tunas, in the eastern tropical Pacific Ocean. By predicting the location of fish aggregations using measurements of environmental properties, fisheries managers may implement dynamic management strategies, with a synoptic level of control, to better conserve and maintain a sustainable yield of the fishing resources. In that regard, satellite remote sensing provides a unique set of tools for fisheries scientists and oceanographers for better understanding of ecological responses through better upper-ocean monitoring on relevant scales since it measures oceanic parameters of habitat and ecosystems that influence fishing resources at spatial and temporal resolutions that are not possible to attain any other way.

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