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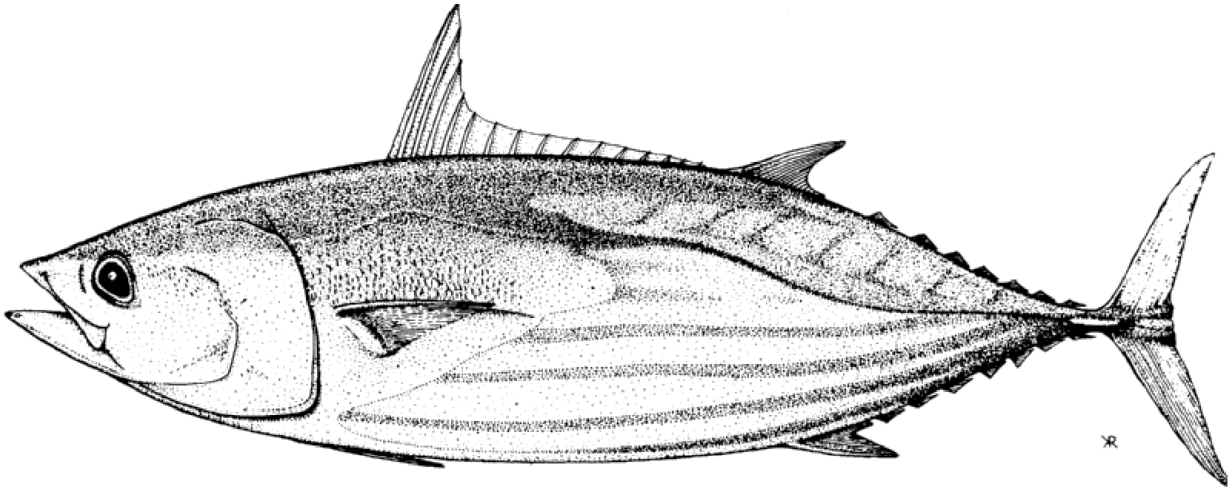
Impacts of the El Niño Southern Oscillation on tuna populations and fisheries in the tropical Pacific Ocean



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1. Introduction

In 1998, the total Pacific Ocean tuna catch was estimated at 2,281,444 mt, that is 67% of the provisional estimate of world tuna catch (3,400,121 mt). The western Central Pacific Ocean (WCPO) catch of tuna fisheries accounted for an estimated 77% of the total Pacific catch, comprising the catch of purse seine (65%), pole-and-line (15%), longline (11%) and artisanal tuna fisheries (Hampton et al., 1998). Important interannual fluctuations have been observed in these fisheries, more or less in apparent correlation with the ENSO events as indicated by the SOI. However, it is often difficult to clearly demonstrate such correlation because several causes can be responsible for observed interannual fluctuations.

From a general point of view, to answer the question why the abundance of tuna species has changed in a given time and space, we have to consider three categories of factors: factors related to changes in fishing techniques that cause changes in species catchability (e.g., changing the depth exploited by the longline), environmental factors inducing spatial changes in the distribution and movements of fish, both in the vertical and horizontal dimensions (e.g., in relation to the depth of the thermocline, or the seasonal or ENSO-related extension of warm waters), and finally real changes in abundance of the stock, with low or high levels of recruitment, in relation either to an environmental change or to the size of the spawning stock biomass (stock-recruitment relationship). In the latter case however, it is generally admitted that, given their very high fecundity and extensive spawning seasons and areas, tropical tunas do not exhibit a marked stock-recruitment relationship. In addition to this intricacy, investigating ENSO impacts can be complicated, as there is an autocorrelation in the frequency of events, i.e., an El Niño is frequently followed or preceded by a La Niña with a frequency oscillating between 3 to 6 years. Therefore, it is necessary to consider long time-series of data for investigating cross-correlation or spectral analyses, all the more since responses to potential changes related to ENSO can be delayed through the repercussions in the population structure. Nevertheless, the following analysis examines some of the evidence of ENSO impacts on tuna fisheries, trying to distinguish which factors are the most affected by the environmental changes linked to these interannual fluctuations.

2. Overview of major ENSO-related oceanographic changes in the equatorial Pacific

ENSO is an irregular low-frequency oscillation between a warm (El Niño) and cold (La Niña) state, that evolves under the influence of the dynamic interaction between atmosphere and ocean. The warm waters in the surface layer of the western equatorial Pacific (the warm pool) have a temperature above 28°C year-round, inducing an atmospheric convection connected to the colder eastern Pacific Ocean through the atmospheric Walker circulation. During El Niño events, the warm waters of the warm pool extend far to the east in the central Pacific (Fig. 1). Conversely, during La Niña the warm pool is confined to the extreme west of the equatorial Pacific. These zonal (east-west) displacements of the warm pool are accompanied by changes in the Walker circulation that are reflected by the Southern Oscillation Index (SOI), calculated from the difference in Sea level Pressure between Tahiti and Darwin. A strong negative index indicates an El Niño while a positive index reveals a La Niña event (Fig. 2). During the last two decades, powerful El Niño events occurred in 1982-83, 1987, 1991-92 and 1997-98, while La Niña events developed in 1981, 1988, and 1998-99. In the following analyses, special attention to spatial effects will be given for the most powerful El Niño events of 1982 and 1997 and the preceding or following La Niña events of 1981 and 1998 by examining the data in the last quarter of these respective years. For simplicity these periods will be called Niño82, Niño97, Niña81 and Niña98.

The intense atmospheric convection associated with the warm pool results in a large excess of precipitation compared to evaporation. Consequently, the warm pool contrasts with the central equatorial water masses by having warmer waters and relatively lower salinity. In this region, the balance between precipitation and entrainment of subsurface saltier water results in haline stratification: a structure called the barrier layer (Lukas and Lindström 1991) appears when the isohaline layer is shallower than the isothermal layer. The barrier layer lies between the bottom of the density mixed layer and the top of the thermocline.

A major consequence of this haline stratification is the inhibition of the downward penetration of energy generated by the westerly wind bursts occurring in the western Pacific. This results in a trapping of westerly wind burst momentum in the surface layer (Vialard and Delecluse 1998), giving rise to strong fresh eastward equatorial currents. This surface layer zonal advection affects the extent of the warm pool and appears to be a major process in the development of El Niño events (McPhaden and Picaut 1990; Delcroix et al. 1992; Picaut and Delcroix 1995; Picaut et al. 1997; Delcroix 1998). The intermittent eastward surface flow in the western Pacific generated by these wind bursts encounters the westward advection of the equatorial circulation and induces a convergence zone on the eastern edge of the warm pool, identified by a salinity front or more approximately by the 29 or 28.5°C isotherm. In an average situation, this convergence zone oscillates around longitude 180°, but spectacular zonal displacements occur in correlation with the ENSO signal, sometimes over 50° of longitude. These displacements can occur rapidly (i.e., with speed >10 cm/s).

Contiguous to the warm pool, the equatorial upwelling in the central and eastern Pacific is generated by the trade winds that result in a vertical circulation bringing toward the surface relatively cold and nutrient-enriched deep water. This equatorial divergence occurs within a mean westward zonal flow, the South Equatorial Current (SEC). This pattern induces a shallow thermocline (~ 50 m) in the eastern Pacific that deepens progressively westward (~150 m in the warm pool). However, during the eastward displacement of the warm water masses accompanying an El Niño, the thermocline deepens in the central and eastern Pacific while it rises abnormally in the western Pacific.

The biological consequence of the equatorial upwelling is a large zonal band with high primary production frequently called the cold tongue, and that contrasts with the generally low primary productive waters of the western Pacific. However, the primary productivity in the western Pacific is strongly affected by ENSO variability as shown on Figure 3. This figure represents the composite images of phytoplankton pigment concentration derived from CZCS satellite data for the 1982-83 ENSO and SeaWiFS satellite data for the most recent event of 1997-99. They reproduce contrasting El Niño and La Niña events situations. In a La Niña or normal situation, a rich (mesotrophic) chlorophyll cold tongue is clearly visible, extending as far west as 160°E, while the warm pool from Philippines to 160°E is typically in a low primary productivity situation (oligo- to ultra-oligotrophic). During the development of El Niño events, the cold tongue retreats east of the date line in an eastward movement accompanying the warm waters extend to the central Pacific and the displacement of the atmospheric convective zone associated with these warm waters. This displacement is associated with a decreasing intensity in equatorial upwelling and primary production.

During the same period, stronger wind stresses occur in the western Pacific, while the barrier layer vanishes or shifts eastward (Vialard and Delecluse 1998). This situation appears to be favourable for an increase of primary production in this region that is clearly seen on Figure 3. In addition to this general pattern, the SeaWiFS ocean color satellite data show a large phytoplankton bloom in the eastern equatorial region of the Indian Ocean at the same period. Also, before the last El Niño abruptly ended in mid-1998, a large phytoplankton bloom developed on the Equator near 165°E during April-May 1998, coinciding with the disappearance of the barrier layer and easterly wind-anomalies (Murtugudde et al. 1999).

3. *Pacific tuna fisheries and ENSO*

3.1. Spatial distribution of fishing data

The purse seine fisheries in the tropical Pacific Ocean target mainly skipjack and yellowfin, and include an eastern and western fishery, roughly separated by the longitude 150°W. The eastern Pacific Ocean (EPO) fishery has a long history and has been managed by the Inter-Tropical Tuna Commission since 1950. A feature of this fishery has been the fishing on dolphin-associated schools that yield good catches of adult yellowfin tuna. This fishery shown some decline since the 1990s, concurrently with the development of the western WCPO fishery and the closing of the US market to tuna caught with dolphins. In contrast to the EPO fishery, there are no dolphin-associated schools in the WCPO, but skipjack is the main catch (~ 70–75% of the total purse seine catch). The majority of the western purse seine catch is taken by the four main DWFN (Distant Water Fishing Nations) fleets Japan, Korea, Taiwan and USA.

Spatial distributions of purse seine catch during ENSO events are presented in Figure 4. Although the fishery was not yet well developed in the WCPO during the 1981-83 ENSO episodes, the eastward spatial shift during El Niño in this region is already visible. This spatial shift that follows the eastward extension of the warm pool has been well demonstrated (Lehodey et al. 1997; Figure 5), and the situation in Niño97 shows this classical pattern. In addition, the proportion of yellowfin in the catch appears very high during this period. However, there is an atypical situation during Niña98. First, because the level of catch in the second half of 1998 was exceptional, and also since most of this catch was coming from a small area centred at 165°E (0-5N, 160-170E) instead of the usual “La Niña fishing ground” west of 150°-160°E. We note also that this very high record of catch occurs despite the maximum deepening of the mixed-layer that affect this area during La Niña events. Therefore, the supposed negative effect on the vulnerability of the stock due to this deepening that increases the vertical habitat of the surface tuna species (skipjack and young yellowfin) and hence decreases their catchability, is not immediately obvious. On the other hand, the location of this exceptional catch corresponds with the area where another exceptional event occurred 6 to 9 months before, that is the phytoplankton bloom shown on Figure 3.

Although contributing much less to the total catch than the purse seine fishery, the pole and line fishery is interesting because it provides a long fishing data time series (particularly the Japanese fleet) and extensive coverage in the WCPO. Also, the fishing technique was not affected by major changes and the abundance index provided by the CPUE (catch per unit of effort) is likely one of the most informative (less biased) within the various tuna fisheries.

Figure 6 shows that in Niña81 the extension of the pole and line fishery is limited in the equatorial zone by the 28°C isotherm with its typical westward penetration along the equator highlighting the presence of a well developed cold-tongue. During Niño82, this limit is shifted eastward, where the fleet achieved exceptional catch rates, with an increasing proportion of yellowfin. Good catch rates in the extreme east of the fishing ground are also apparent in Niño97, although the fishing effort deployed has declined, a general trend in the past decade with the concurrent development of the purse seine fishery. It is also worth noting that as for the purse seine fishery, the deepening of the mixed-layer has apparently no effect. Unfortunately, fishing data were not yet available for the strong 1998-99 La Niña event.

The longline fishery provides the longest time series of catch estimates for the WCPO, with estimates available since the early 1950s (Lawson, 1999). The annual total longline catch has been relatively stable during the past 25 years, with total catches generally between 150,000 and 200,000 mt (Hampton et al, 1999). There have been significant changes in fleet operations during the past two decades. For example, a feature of the 1980s was a change in targetting practices, mainly by increasing the fishing depth of longlines, in order to capitalise on a higher price for bigeye over yellowfin. Most of the longline catch in the Pacific is taken by the large vessel distant-water fleets of Japan, Korea and Taiwan. Effort by these fleets is widespread as they target bigeye and yellowfin for the frozen sashimi market, and albacore in the more temperate waters for canning.

Spatial distribution of Japanese longline CPUE is shown on Figure 7 for Niño81, Niña82, and Niño97. The most striking changes are spatial distributions of high and low CPUE in the Equatorial band 5°N-15°S, with an increase of the bigeye catch ratio in the western Pacific during the last event.

3.2. Temperature habitats

Given these spatial distributions, the ENSO impacts on the tuna fisheries were investigated in four different geographical boxes identified as: the Western Equatorial Pacific (W: 120°E-165°E; 10°N-10°S), the Central Western Equatorial Pacific (CW: 165°E-150°W; 10°N-10°S), the Central Eastern Equatorial Pacific (CE: 150°W-125°W; 0°N-20°S) and the Eastern Equatorial Pacific (E: 125°W-80°W; 0°N-20°S). These boxes are outlined in

Figure 7. Environmental and fishing data have been aggregated in these boxes. Temperature data were extracted from the OGCM outputs developed by the National Center for Environmental Prediction (NCEP) (Ji and Smith 1995), and the depth of the mixed-layer is approximated by the depth where temperature = SST-1^{o}C.

The time-series for these four regions are shown in Figure 8 for the sea surface temperature (SST), the mixed-layer and the depth of the 15^{o}C isotherm, and the relation between SOI and these parameters are in Figure 9. In the western region, the SST is mainly marked by the seasonal signal. However, there is also an interannual variation related to ENSO, but with a low amplitude (~1^{o}C). In the western central region, the SST variability is clearly related to ENSO, with the major impact during La Niña when the cold tongue penetrates far to the west and produces a large decrease of SST. It is interesting to note that the SST interannual fluctuation in the west, i.e. positive anomaly during la Niña and negative anomaly during El Niño, is in opposite phase with SST anomaly in the central western area. On the vertical structure, the depths of the mixed-layer and the isotherm 15^{o}C fluctuate in synchrony with the ENSO signal in both regions, rising during El Niño and deepening during La Niña with a maximum amplitude of 30-40 m, but with a mixed-layer always shallower in the western central region. However, the fluctuation of the mixed-layer in the western central region would be delayed by ~3 months relatively to the western region (Table 1). It is important to note the synchrony or the time lags previously described between SOI and thermal structure changes to consider potential effects of these changes on catch vulnerability.

In both eastern regions, the SST fluctuates in synchrony and is mainly marked by the seasonal signal, with higher amplitude in the east. The superimposed interannual variability, that appears clearly only for the most powerful El Niño (1982-83, 1986-87, 1997-98), is correlated to SOI with one month lag (Table 1). Similarly, the mixed-layer variability is dominated by the seasonal signal. The interannual signal is very low in the east and marked only for the most powerful El Niño in the central eastern area with a shallower depth during El Niño. The effect on the depth of isotherm 15^{o}C is more clear in the eastern region with a large deepening (~40 m) associated with minimum peaks of SOI (El Niño).

In summary, the major changes observed in the vertical thermal structure are:
- a strong seasonal signal in the eastern and central eastern region, both for SST and mixed-layer,
- no marked ENSO-related change in the central eastern region.

During El Niño events:
- a general “shallower” thermal structure in the western and central western areas, particularly well marked and correlated with SOI in the western region, and with a potential delay of 3 months between the two regions
- an important deepening of the thermal structure below the mixed-layer in the eastern region.

The effects are opposite during La Niña events.

To help in analysing how these temperature changes can affect the vertical and horizontal distribution of tuna species, a temperature habitat was defined for the four tuna species, skipjack, yellowfin, bigeye, and albacore. Temperature functions have been defined for these species (Figure 10) according to the knowledge on the relationships between tuna physiology, distribution and ambient temperature. Such relations have been studied in laboratory experiments, by *in situ* tracking experiments and by comparisons between catch statistics and oceanographic conditions (e.g., Sharp and Dizon 1978, Forsbergh 1980, Matsumoto et al. 1984, Brill 1994, Barkley et al. 1978). Using the function temperatures, zonal and meridional sections of habitat were calculated and are presented on Figure 11. They will be used in the following time series analysis.

3.3. CPUE time series

Tuna catch rates per unit of effort (CPUE) have been calculated in the four geographical boxes for the Japanese pole and line (Figure 12), the Japanese and U.S. purse seine fleets (Figure 13), and the Japanese longline fleets. Theoretically, factors previously described that can affect the CPUE should have different effects on the time series fluctuations. Changes in catchability due to a modification of the vertical thermal structure should be identified by a direct correlation between CPUE and temperature variable or SOI (eventually with the same lag that occurs between SOI and the temperature variable). Note that it is interesting to use the SOI series since the environmental data series start only in year 1980. The change should also be coherent amongst the different geographical boxes. Changes due to horizontal movements (Figure 5) may be identified by some recurrent delay patterns between CPUE of different regions. Finally effects on recruitment should appear with delays consistent with the age of the first classes recruited in the fishery.

- Direct correlation in relation with the vertical structure

For the pole and line fleet, there are some periods of time where low and high skipjack CPUE coincide with El Niño and La Niña events respectively, but it is not a constant feature, e.g., there is a high peak of CPUE in 1984 in a normal situation and in 1991-92 during an El Niño phase. Similarly for the purse seine fleets, although the 1997-98 El Niño peak for the SOI coincides with low peak of skipjack CPUE in both fleets, this is not a general pattern, and high skipjack CPUE can occur during normal or even La Niña phases. Since the fluctuations are not consistently correlated to the ENSO signal, the environmental changes in the vertical thermal structure directly linked to SOI likely have likely a low influence on the skipjack catchability (at least at the scale of the fishery), or the impact is masked by much more large fluctuations due to other factors (i.e., horizontal movement or stock abundance). The example of temperature habitat for skipjack in Figure 11 shows effectively that the major change is a horizontal extension or contraction of the skipjack habitat during El Niño and La Niña phases respectively.

Yellowfin CPUE of the pole and line fishery is much lower than for skipjack but shows interesting large fluctuations (Figure 12). Considered together with the purse seine CPUE time series, there is a general coherent pattern with higher CPUE during El Niño in the both western areas. For the three fleets, cross-correlation is negative, direct in the western area and with a lag of 2-3 months in the central western area, consistently with the lag observed in the rising of the vertical thermal structure between these two regions. Therefore, the rising (deepening) of the mixed-layer depth related to El Niño (La Niña) is associated with an increasing (decreasing) pole and line and purse seine CPUE of yellowfin in both western and central western regions but with a concomitant delay of ~2-3 months. The rising is associated with a vertical extension of the vertical temperature habitat as shown on Figure 11.

Before analysing the ENSO variability of the Japanese longline fishery, it is interesting to consider the general trends due to the transition from the regular shallow longline, e.g. in the first decade of the series, to the deep longline, e.g. in the last decade. This change in the fishing technique resulted in a large increase of bigeye CPUE in the western region, while there is no apparent strong effect in the other regions. In the same time, the yellowfin CPUE was reduced in the western area. These mirrored changes can likely be attributed to the difference in the vertical extension of the bigeye and yellowfin habitat; while the two habitats are overlapping, bigeye are distributed deeper than yellowfin (Figure 11). Therefore, we can expect that the effect of ENSO-related changes in thermal structure, and hence in the vertical extension of the tuna habitats, will produce similar fluctuations in the CPUE (under the assumption that fishermen do not change the longline depth accordingly to the ENSO situation). However the bias introduced in the time series by the change in the fishing technique makes it difficult to observe significant cross-correlation through statistical analyses.

Nevertheless, it seems possible to draw some coherent pattern in the west (Table 1). In the two western regions, El Niño (La Niña) events would have a positive (negative) effect on bigeye CPUE, and conversely a negative (positive) effect on albacore CPUE. In parallel to these statistical results, the temperature habitats on Figure 11 show during El Niño a vertical extension for bigeye and a rising of the very narrow habitat for albacore in the west (between 10^{o}N-10^{o}S). In the eastern areas, results are ambiguous, since there is a correlation in the central eastern box indicating a positive El Niño direct effect on yellowfin longline CPUE, while in the eastern box the CPUE increases when the depth of isotherm 15^{o}C decreases, i.e. during La Niña events. The temperature habitat in the east shows a slight contraction and deepening of the yellowfin vertical temperature habitat during El Niño events, that would be consistent with a negative direct effect on the catch rate.

- Delayed correlation in relation to horizontal movements

Under the hypothesis that the spatial zonal displacements observed for skipjack would have a major impact on its abundance level in the two western regions, we should observe a delayed or even opposite phase between fluctuations of their CPUE. The US purse seine series shows effectively an opposite pattern between western and central western areas in 1989 and 1995, but it simply reflects a very low or null fishing effort in the central area during La Niña or normal situations, consistent with the westward spatial shift associated to these periods. The general pattern that emerges from the three series is a fluctuation of skipjack CPUE in phase between the two regions (Table 2, Figure 12 and 13). Therefore, the impact on the CPUE of spatial movements of skipjack observed between western and central Pacific during ENSO events would be usually masked by another larger source of variability.

Contrary to skipjack, the fluctuations of yellowfin and bigeye CPUE are not always in synchrony between the four defined geographical boxes, especially for the longline fleet (Table 2, Figure 12 and 13). However, it is difficult here to dissociate the effects between horizontal and spatial movements.

- Delayed correlation in relation to recruitment

Concerning skipjack, large fluctuation in stock size, i.e. recruitment, is a major potential explanation for the CPUE fluctuations. It is interesting to note that a recurrent pattern in the time-series is a peak of high CPUE in the 6 to 12 months following an El Niño event. This is reflected by the significant cross-correlation between SOI and the Japanese purse seine skipjack CPUE time series for the western area (R= -0.314, lag 8 months). The pole and line series also gives a negative correlation (Table 1) but with a lag of 14 and 18 months in the western and central western regions respectively. Skipjack of 50-60 cm (age 14-20 months) are usually the main size class in the WCPO pole and line catch, while the first size class of the purse seine catch is smaller (35 cm, ~9 months). Therefore, these lags are coherent with a positive effect of El Niño on the recruitment.

The cross correlation between SOI and pole and line series gives a positive but low correlation in the central western Pacific for yellowfin with a lag of 19 months, i.e., an opposite signal compared to skipjack (Table 1). For the longline there is also a positive correlation in the eastern region with a lag of 14 months. At age 14 months, yellowfin reach ~ 75 cm, that is the first size class of fish recruited in the longline fishery. There is a similar but much lower correlation for bigeye at lag +15 in the same region. These results would suggest a positive impact of La Niña events on the recruitment of these species, particularly in the east. A similar impact has been proposed for the south Pacific albacore, based on estimated recruitment by the length-based, age-structured population dynamic model MULTIFAN-CL (Fournier et al. 1998).

3.4. Summary and hypotheses

If the four main tuna species are influenced by ENSO in the tropical Pacific, the impacts are different according to each species. Large fluctuations in the catch and catch rates of skipjack tuna are driven by changes in stock size, and to a lesser extent by horizontal spatial extension (El Niño) or contraction (La Niña) of the habitat. The warm pool is the major spawning area of skipjack. Therefore, a plausible hypothesis to explain the ENSO effect on skipjack recruitment could be an increase of survival rates of juvenile skipjack correlated to the increase of primary and zooplankton production during El Niño events in this region. The effect will be delayed by 6 to 12 months, at which time skipjack are recruited to the fishery. The exceptional record of skipjack catch in the end of 1998 following the phytoplankton bloom of April-May 1998 provides additional confidence in this scenario, all the more since length frequencies data show an exceptional proportion of small size skipjack (LF: 20-35 cm, age: ~ 5-9 months) in the purse seine catch of the two last quarters of 1998 (Figure 15). If changes in the vertical thermal structure may have some local effect on the catchability, this source of variability is apparently negligible at the scale of the fishery and in regard to the other effects.

This seems not to be the case for yellowfin. Rising and vertical extension of its temperature habitat in the west during El Niño increases the catchability by the surface fishing gears. In the east, El Niño events would have a negative impact on yellowfin longline catch, while the negative effect is also well known on the purse seine fishery. Indeed, the large decline in the catch during the 1982-83 El Niño is one of the main factors responsible of the displacement of the US fleet toward the WCPO. This general negative effect on both surface and deep fishery suggests a horizontal displacement of the resource rather than an effect due to vertical changes. Combined with these vertical and horizontal spatial effects, there would be an ENSO effect on recruitment, apparently opposite in the east to the effect observed for skipjack. However, this latter conclusion is based only on one correlation between SOI and a CPUE time series and is in contradiction with another lower one in the central eastern box.

While most of the total skipjack stock biomass is associated with the warm pool, yellowfin is more widely distributed. The spawning ground also is extended, covering both east and west tropical Pacific. Indeed, it appears that mature yellowfin spawn when SST is above 26°C (Schaefer 1998). Therefore, the simple ENSO-related recruitment mechanisms described for skipjack (higher productivity, lower juvenile mortality, higher recruitment) could be also proposed to explain the positive (negative) delayed effect of La Niña (El Niño) in the east, but they would lead to also predict a positive (negative) El Niño (La Niña) effect in the west. However, given the relationship between sea temperature and spawning, another potential impact of ENSO on the recruitment in the eastern Pacific could be proposed. As a matter of fact, El Niño events largely extend the spawning area in the eastern Pacific (Figure 1) and could create better conditions than during La Niña events for recruitment in this area. At this stage of analysis, no conclusion can be drawn on these different hypotheses on the (opposite) effect of El Niño on the yellowfin recruitment.

Similar conclusions (or lack of conclusions !) on the ENSO effect for yellowfin recruitment can likely be applied to bigeye. However given its deeper habitat, the effects due to vertical changes are slightly different. In the west, a positive (negative) effect on bigeye longline CPUE during El Niño (La Niña) events would be associated mainly with the vertical extension rather than the rising of the habitat. Horizontal movements may also be associated with these changes.

ENSO effects on albacore populations should be more easy to dissociate than for yellowfin and bigeye because of its spatial distribution (two well differentiated south and north stocks) with spawning grounds between about 10 and 25° of latitude and a seasonal (summer) spawning period. The western geographical areas defined for this study were not really well adapted to cover the albacore fishery. However, it is interesting to note in this region the very narrow temperature habitat, that is likely in the upper range exploited by the deep longline, particularly during El Niño events, when CPUE is the lowest. A positive (negative) effect of La Niña (El Niño) on the south albacore recruitment is consistent with the mechanism proposed for skipjack (and maybe yellowfin and bigeye), as the spawning ground is largely under the influence of the productivity of the cold tongue.

4. *Toward an ENSO-related time series forecast ?*

To test the previous conclusions on the potential impacts of ENSO on tuna population and fisheries, a first simple approach is to consider a recruitment directly proportional to the SOI values (multiplied by -1 to have a positive effect of El Niño events). A very simple preliminary (quarterly-based) population model has been used with the growth, mortality and selectivity functions shown on Figure 16. The level of recruitment in the first quarter was defined as 100*SOI (or –1*100*SOI, if El Niño has a positive effect). Spawning occurs during the first quarter of the year for south Pacific albacore, during the first and second quarter for bigeye and during all the year for yellowfin and skipjack. Therefore, artificial fluctuations of stock biomass due to the variation of the SOI values are produced (Figure 16), but without consideration of the impact of fisheries. Already, it is very interesting to note the repercussion of the ENSO effects due to the population structure. While skipjack has a typical interannual variability, the albacore fluctuation could be easily confused with decadal variability. For this latter species, the fluctuation is similar to that provided by the Multifan-CL estimate (Fournier et al. 1998), that shows a biomass slightly increasing in the 1960s with a peak in the mid-1970s, and decreasing thereafter at a level lower than in the 60s. Also, the selectivity can result in opposite fluctuation of abundance between surface or longline gears, as illustrated for yellowfin.

The predicted biomass anomalies have been compared to CPUE of most of the main tuna fisheries in the Pacific. Hypotheses for the ENSO impact on recruitment are a positive El Niño effect in the western Pacific and a positive La Niña effect in the eastern Pacific. It is not possible to present all the comparisons, but some typical cases are presented on Figure 17. There are a few cases with nice apparent correlation between low and high peaks or similar trends between CPUE and the predicted anomaly. However, other comparisons do not fit very well, either over all the series or a part of them.

From the previous analysis, we know that direct effects related to ENSO can also largely affect the CPUE, particularly the change in the vertical structure. It is possible to test a combination of such direct effects with the delayed effect associated with recruitment. As it is correlated to SOI, this is made by multiplying the predicted biomass anomaly by the SOI, and changing the sign according the desired positive or negative effect of El Niño or La Niña situation. However, in this case, a positive effect of El Niño on the recruitment in the population combined with a positive direct effect of El Niño on the catchability will provide the same result as a positive effect of La Niña in the recruitment combined with a negative direct effect of El Niño on the fishery. The new predicted series are presented in Figure 18.

In many cases there is a large improvement in the fit between predicted anomaly and CPUE fluctuations. For the skipjack purse seine series in the western Pacific, it is interesting to note that with the positive effect of El Niño on recruitment, it is necessary to consider a negative direct effect of El Niño for the Korean fleet, and conversely a positive direct effect of El Niño for the US fleet. Rather than an effect due to the change in the vertical structure, it seems possible to envisage an horizontal effect. The Korean fleet operates mainly in the western equatorial region where the abundance of skipjack is potentially reduced during El Niño in relation with an horizontal extension of the skipjack habitat. Conversely, the US fleet appears to follow the displacement of the convergence zone between the warm pool and the cold tongue during the development of an El Niño event, and it is probable that this convergence zone during the zonal movement is favourable to aggregation of skipjack (Lehodey et al., 1997, 1998).

The yellowfin purse seine time series in the western Pacific are also greatly improved. Indeed, the direct effect, likely due to the change in the vertical thermal structure appears to be the dominant signal in this case, and there is a good fit with the CPUE series either when SOI direct relationship is considered alone or when it is combined with a positive effect of El Niño on the recruitment. For the longline fishery in the western Pacific, the hypothesis of a positive El Niño effect both for recruitment of bigeye and its catchability (direct effect due to SOI) in the west provides a good fit and is consistent with the results from the previous time series analysis. In the eastern Pacific, the hypothesis of a positive La Niña effect on the recruitment must be associated to a positive effect of La Niña on catchability to obtain a good fit both for yellowfin and bigeye. However it must be noted that a similar result would be obtain with positive El Niño effects on recruitment and catchability.

5. Conclusion

This very simple modelling approach provides useful results. They would confirm the previous preliminary conclusions and support the hypothesis that ENSO affects the recruitment of skipjack, yellowfin and bigeye tuna with a positive El Niño effect in the western Pacific. Spatial extension of the skipjack habitat during El Niño events would have a negative effect on the catchability in the west, but would increase it in the warm pool – cold tongue convergence zone during the eastward displacement associated to the development of El Niño. A direct positive effect likely related to the vertical change in the thermal structure during El Niño would increase purse seine and pole and line catch of yellowfin and longline catch of bigeye in the western Pacific. Recruitment of albacore seems to benefit from La Niña situation, but more focused analysis should be specifically devoted to this species.

In the eastern Pacific, there is more uncertainty in the conclusions. According to the tests of the modelled time series, two theoretical cases can be considered for yellowfin and bigeye: either a positive La Niña effect on the recruitment and on catchability, or conversely a positive El Niño effects on recruitment and catchability. The statistical analysis in this study did not allow to clearly identify the direct effects of ENSO on the catchability for yellowfin and bigeye and therefore, does not allow to decide between the two hypotheses. Additional analyses are needed for this region. Comparisons with other independent results from modelling and observations are also necessary in both regions. A confirmation of these preliminary results would lead to an increasing capacity in term of forecast linked to the improvement of ENSO predictions.

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Table 1. Cross-correlation analysis between SOI and temperature variables and CPUE time series, and between the depth of isotherm 15^{o}C and longline CPUE time series

			Area box							
var1	var2	fleet	W		CW		CE		E	
SOI	SST		0.54	(+0)	-0.68	(+0)	-0.89	(+1)	-0.72	(+1)
	Mixed-layer		0.73	(+1)	0.75	(+3)				
	Iso 15oC		0.74	(+3)	0.58	(+5)	-0.49	(-1)	-0.72	(+2)
	Skipjack	PL-JP	-0.2	(+14)	-0.43	(+18)				
	Skipjack	PS-JP	-0.33	(+8)						
	Skipjack	PS-US								
	Yellowfin	PL-JP	-0.33	(+1)	-0.37	(+2)				
					0.21	(+19)				
	Yellowfin	PS-JP	-0.42	(+0)						
	Yellowfin	PS-US	-0.27	(-1)	-0.35	(+3)				
	Yellowfin	LL-JP					-0.30	(-1)	0.45	(+14)
	Bigeye	LL-JP	-0.32	(-3)	-0.59	(+0/+1)			0.19	(+15)
	Alb	LL-JP								
Iso 15oC	Yellowfin	LL-JP							-0.51	(+0/+3)
	Bigeye	LL-JP	-0.32	(+0/-3)						
	Alb	LL-JP	0.32	(+0/+1)	0.22	(+0/+1)				

Table 2. Cross-correlation analysis between CPUE of same fleets in the different geographical boxes

			area box					
		fleet	CW		CE		E	
W	Skipjack	PL-JP	0.68	(+1)				
	Skipjack	PS-JP	0.45	(+0)				
	Skipjack	PS-US	-	-				
	Yellowfin	PL-JP	0.27	(+1)				
	Yellowfin	PS-JP	0.33	(+0)				
	Yellowfin	PS-US	-	-				
	Yellowfin	LL-JP	0.26	(+0)	-	-	-0.30	(+2)
	Bigeye	LL-JP	0.62	(+0)	-	-	-	-
	Alb	LL-JP	-	-	-	-	-	-
CW	Yellowfin	LL-JP			0.34	(+4)	-	-
	Bigeye	LL-JP			0.47	(+5)	0.34	(+2)
	Alb	LL-JP			-	-	-	-
CE	Yellowfin	LL-JP					0.29	(-1)
	Bigeye	LL-JP					0.74	(-3)
	Alb	LL-JP					-	-

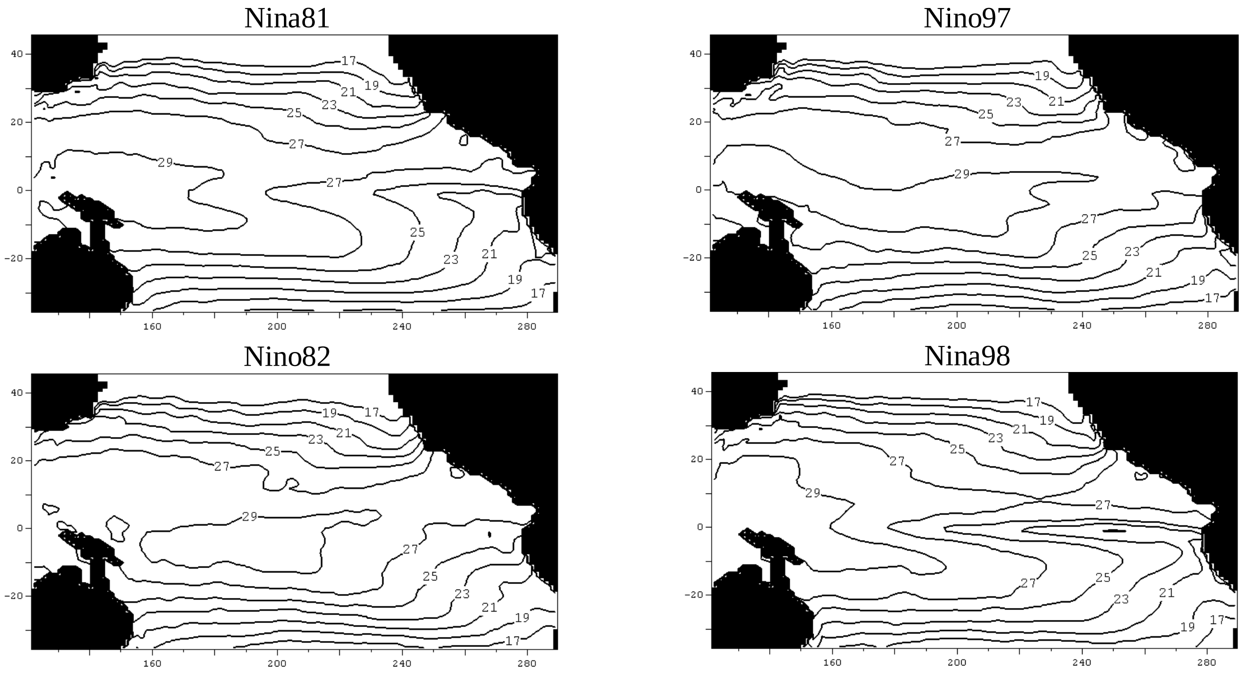


Figure 1. Sea Surface temperature during the last quarter of 1981 (Niña81), 1982 (Niño82), 1997 (Niño97), and 1998 (Niña98)

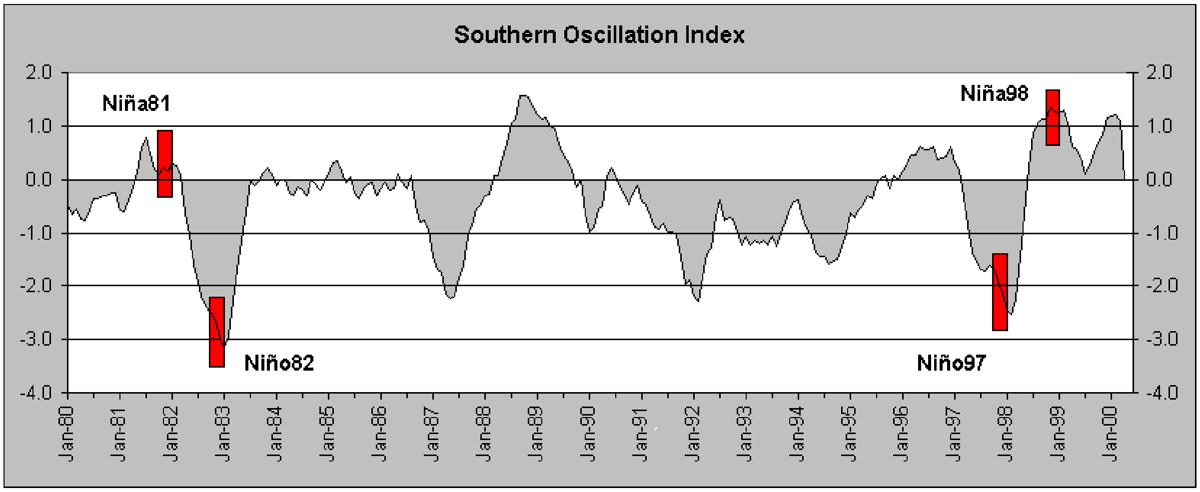


Figure 2. Southern Oscillation Index since 1980 with the four time periods of ENSO events considered in the study

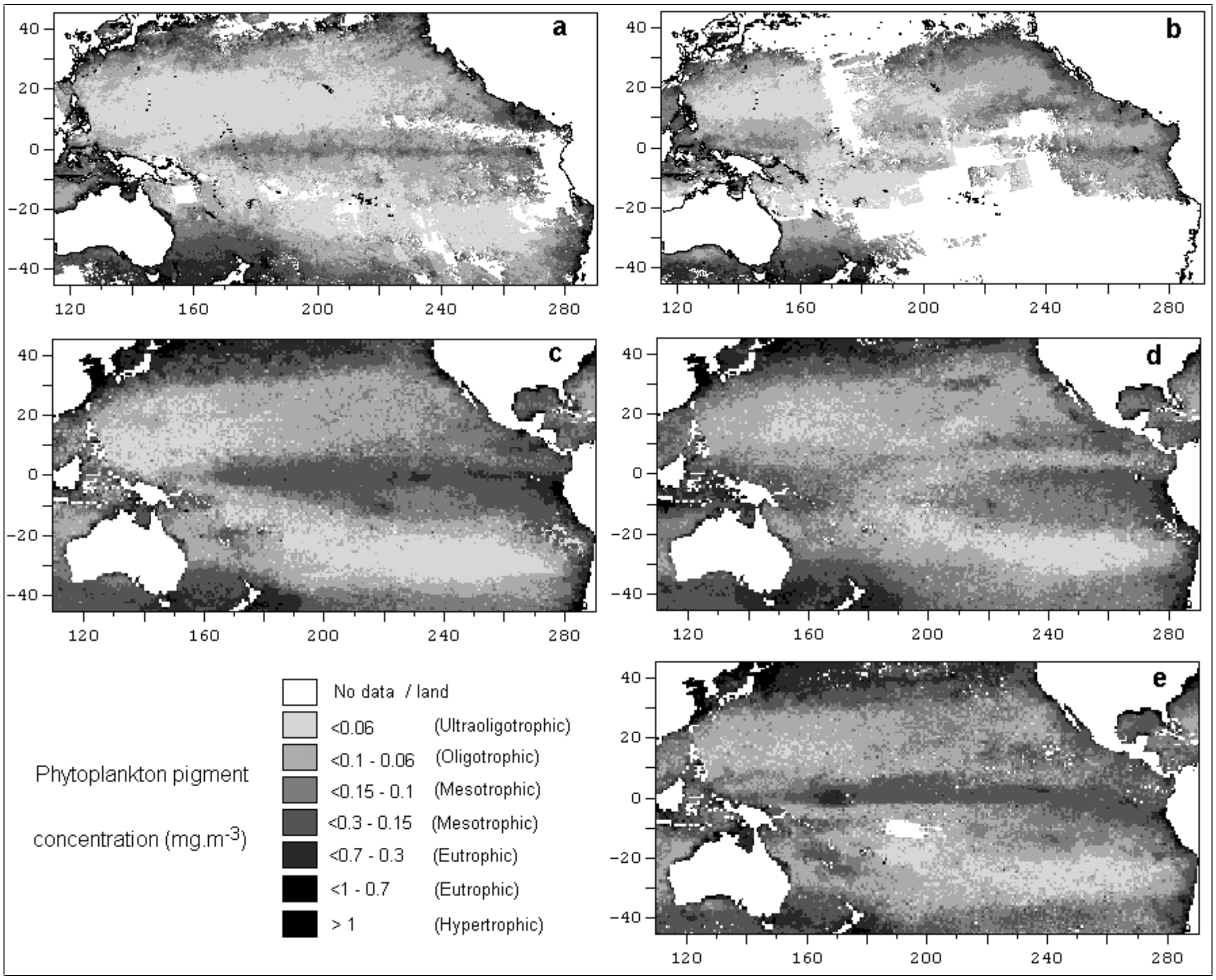


Figure 3. Primary production in the Pacific Ocean. Composite images of satellite-derived phytoplankton pigment concentration. **a**: CZCS image for September to December 1981 (normal- La Niña-like phase), **b**: CZCS image for November 1982 to February 1983 (El Niño phase), **c**: SeaWiFS image for October to December 1998 (La Niña phase), **d**: SeaWiFS image for September to November 1997 (El Niño phase), **e**: SeaWiFS image for April-May 1998 (El Niño phase).

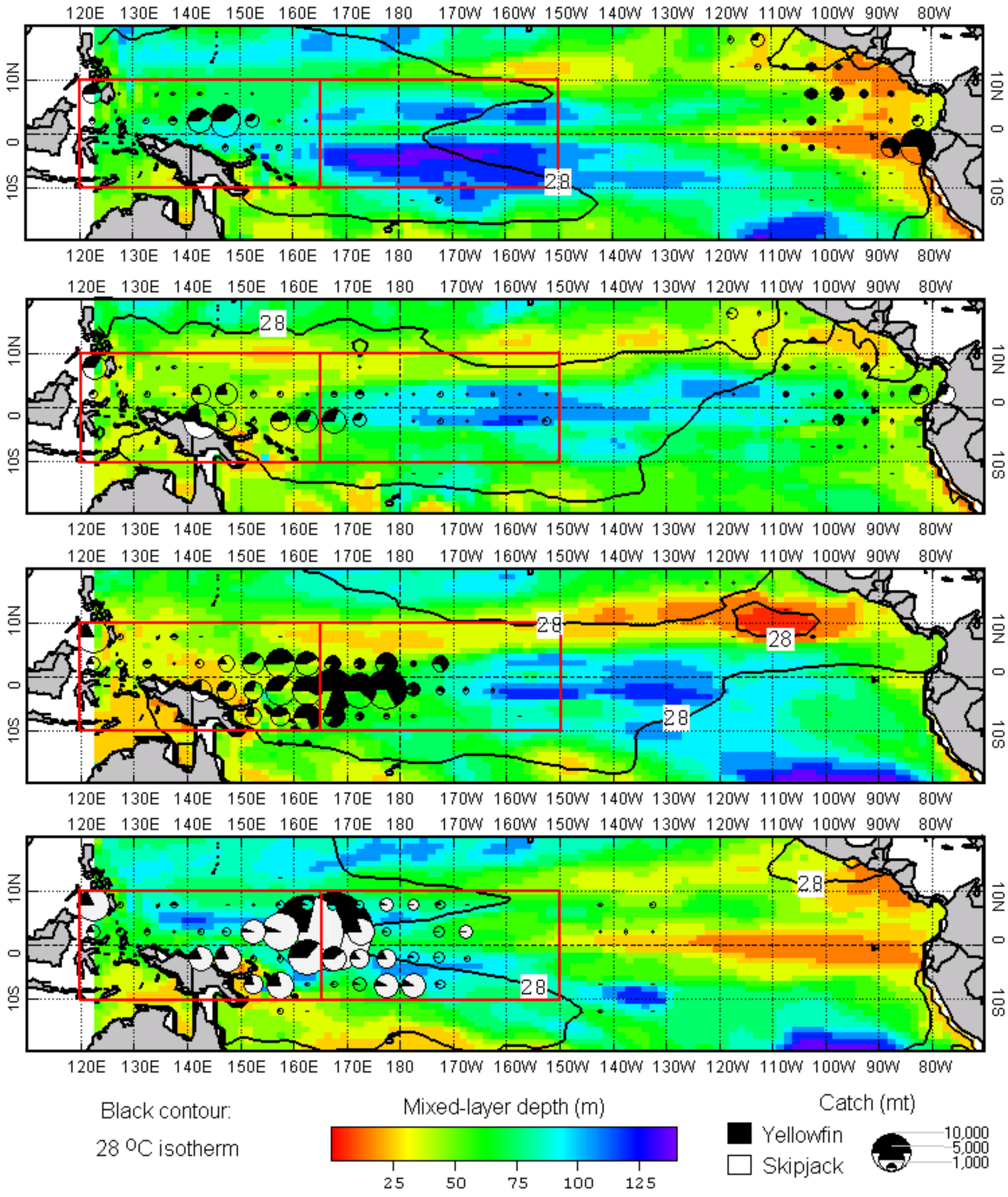


Figure 4. Purse seine catch during the last quarter of 1981 (Niña81), 1982 (Niño82), 1997 (Niño97), and 1998 (Niña98) with the mixed-layer depth and the SST 28oC isotherm

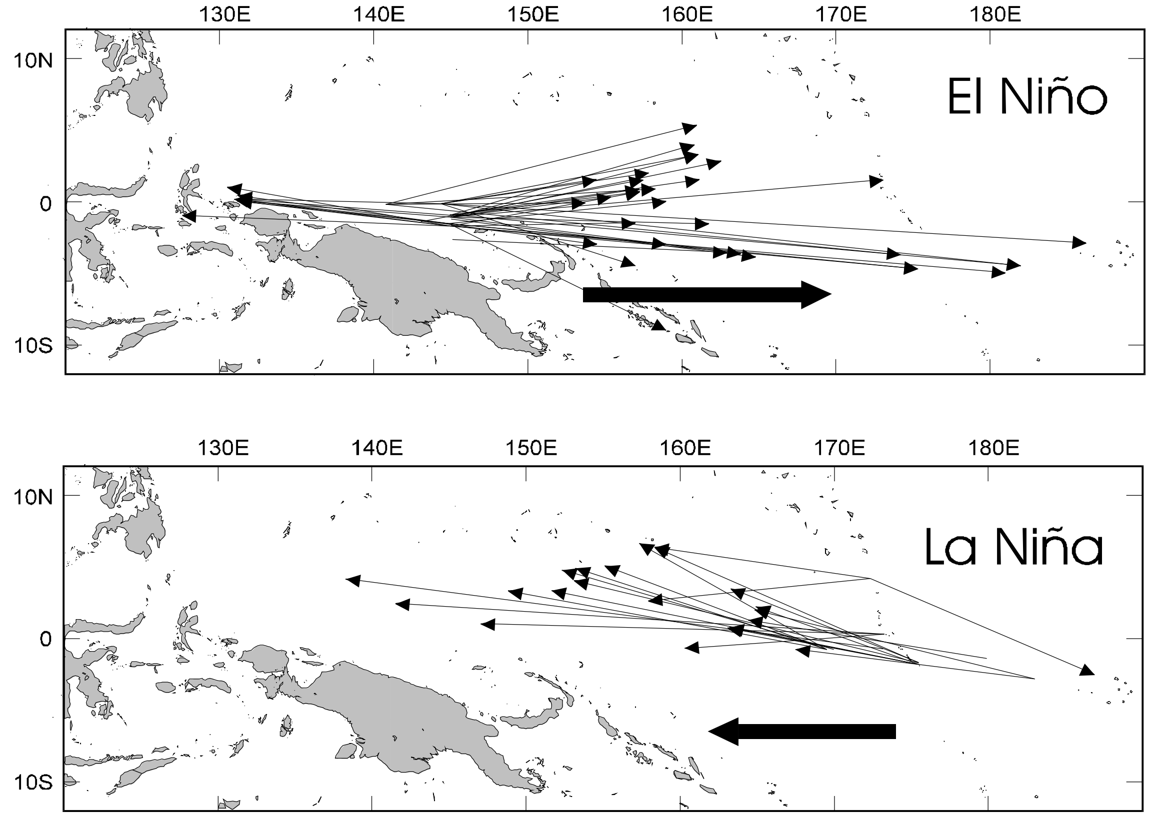


Figure 5. Displacement of tagged skipjack tuna. Tagging data were compiled from records of a large-scale tagging programme carried out by the Secretariat of the Pacific Community (redrawn from Lehodey et al. 1997).

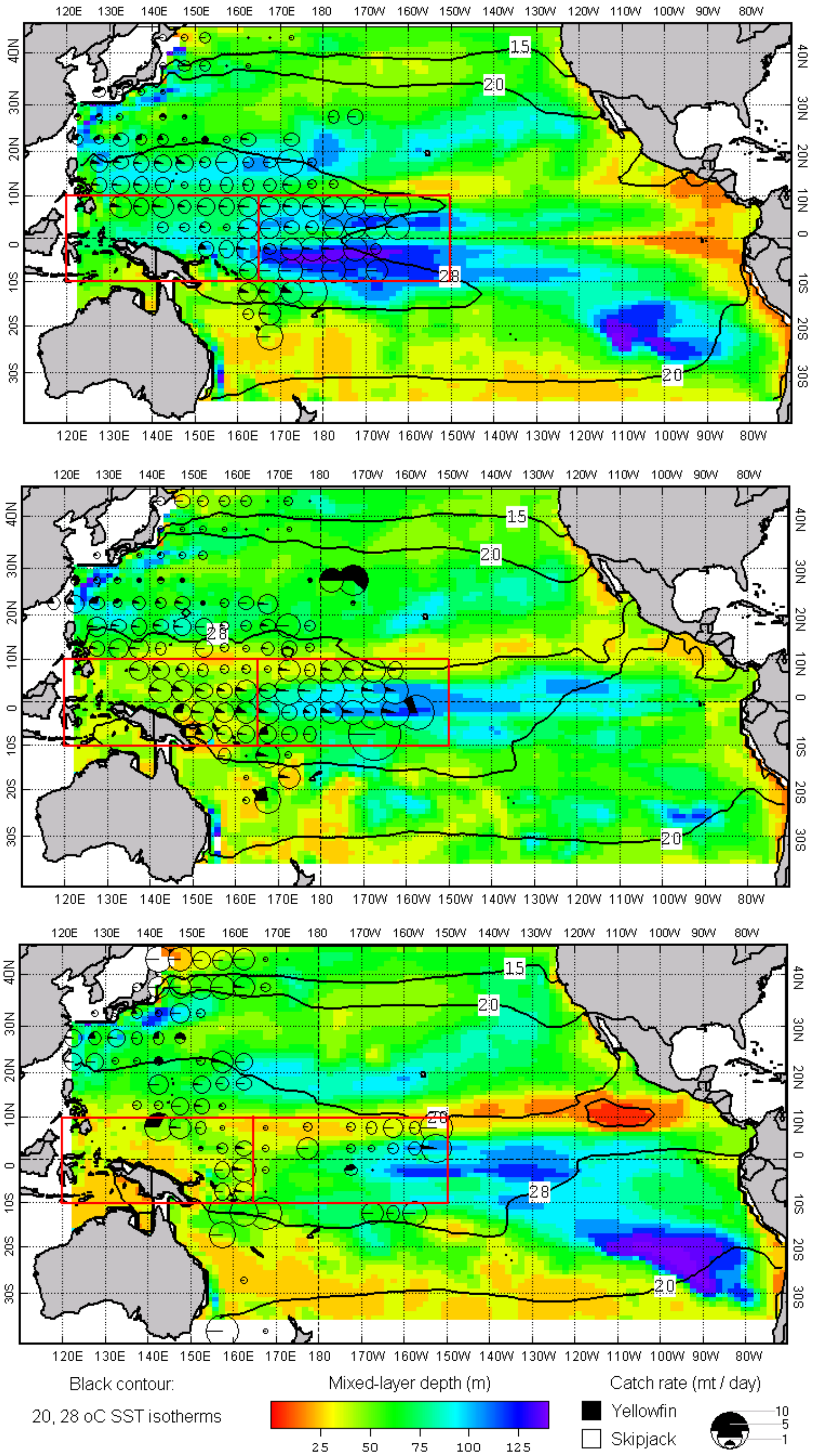


Figure 6. Catch rate of the Japanese pole-and-line fleet for yellowfin and skipjack during the last quarter of 1981 (Niña81), 1982 (Niño82), and 1997 (Niño97), with the mixed-layer depth and the 20, 28oC SST isotherm

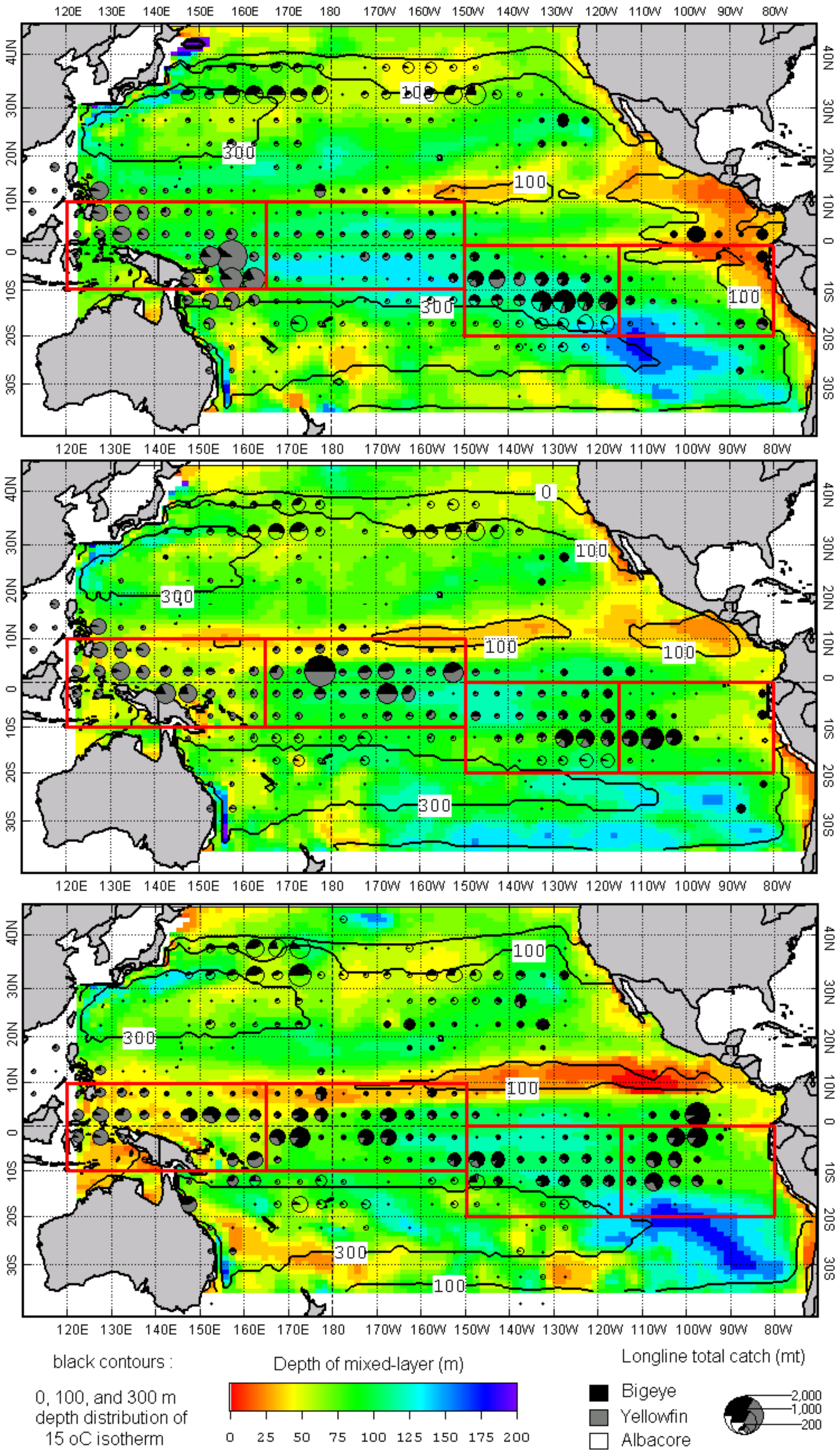


Figure 7. Total catch by longline of yellowfin, bigeye and albacore during the last quarter of 1981 (Niña81), 1982 (Niño82), and 1997 (Niño97), with the mixed-layer depth and the depth of 15^{o}C isotherm

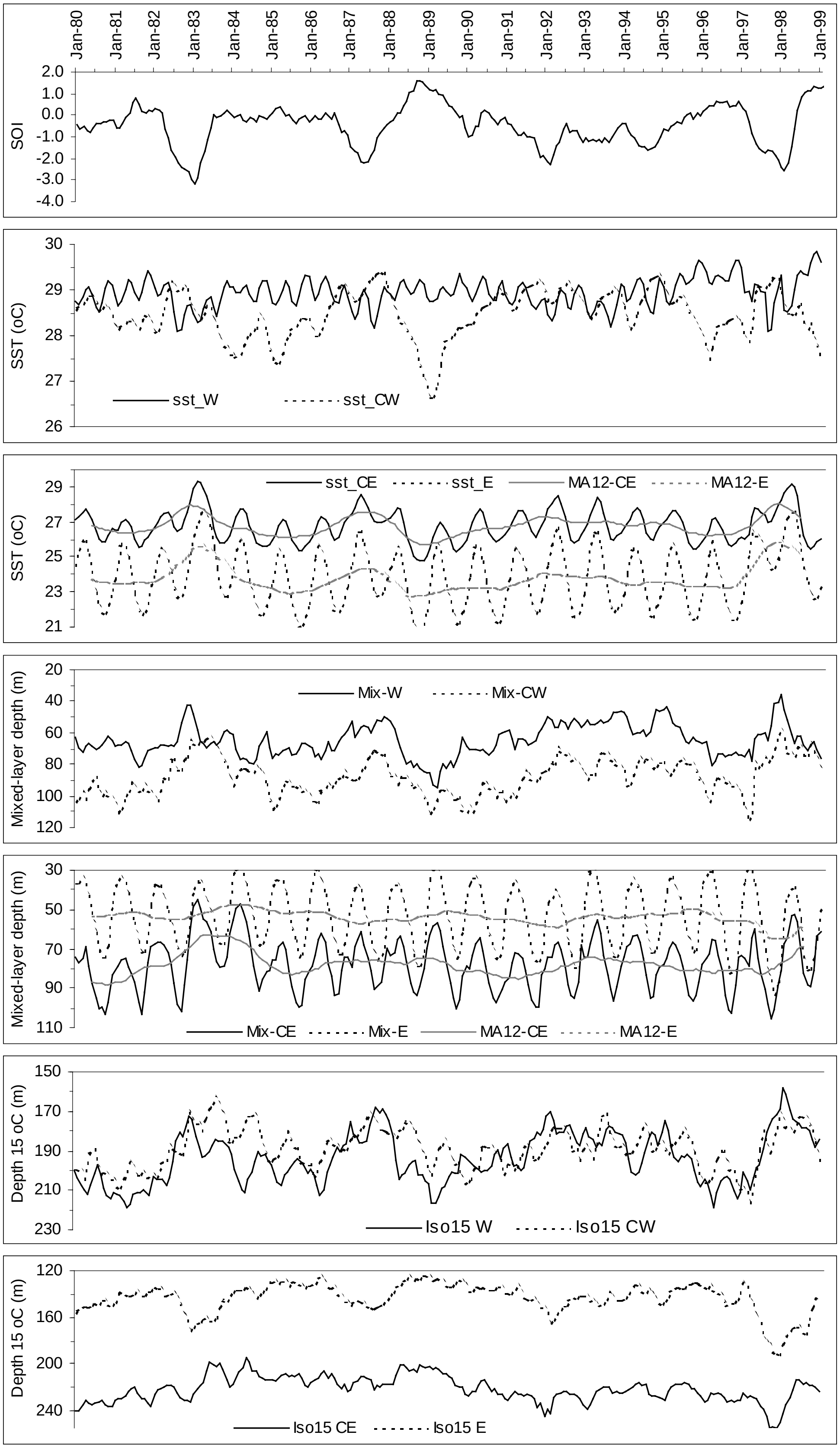


Figure 8. Time series of SOI, SST, depths of the mixed-layer(Mix) and of the 15^{o}C isotherm (Iso 15) for the four geographical boxes, W (120^{o}E-165^{o}E, 10^{o}N-10^{o}S), CW (165^{o}E-150^{o}W, 10^{o}N-10^{o}S), E (150^{o}W-115^{o}W, 0^{o}N-20^{o}S), and CE (115^{o}W-80^{o}W, 0^{o}N-20^{o}S). MA12 is moving average on 12 months.

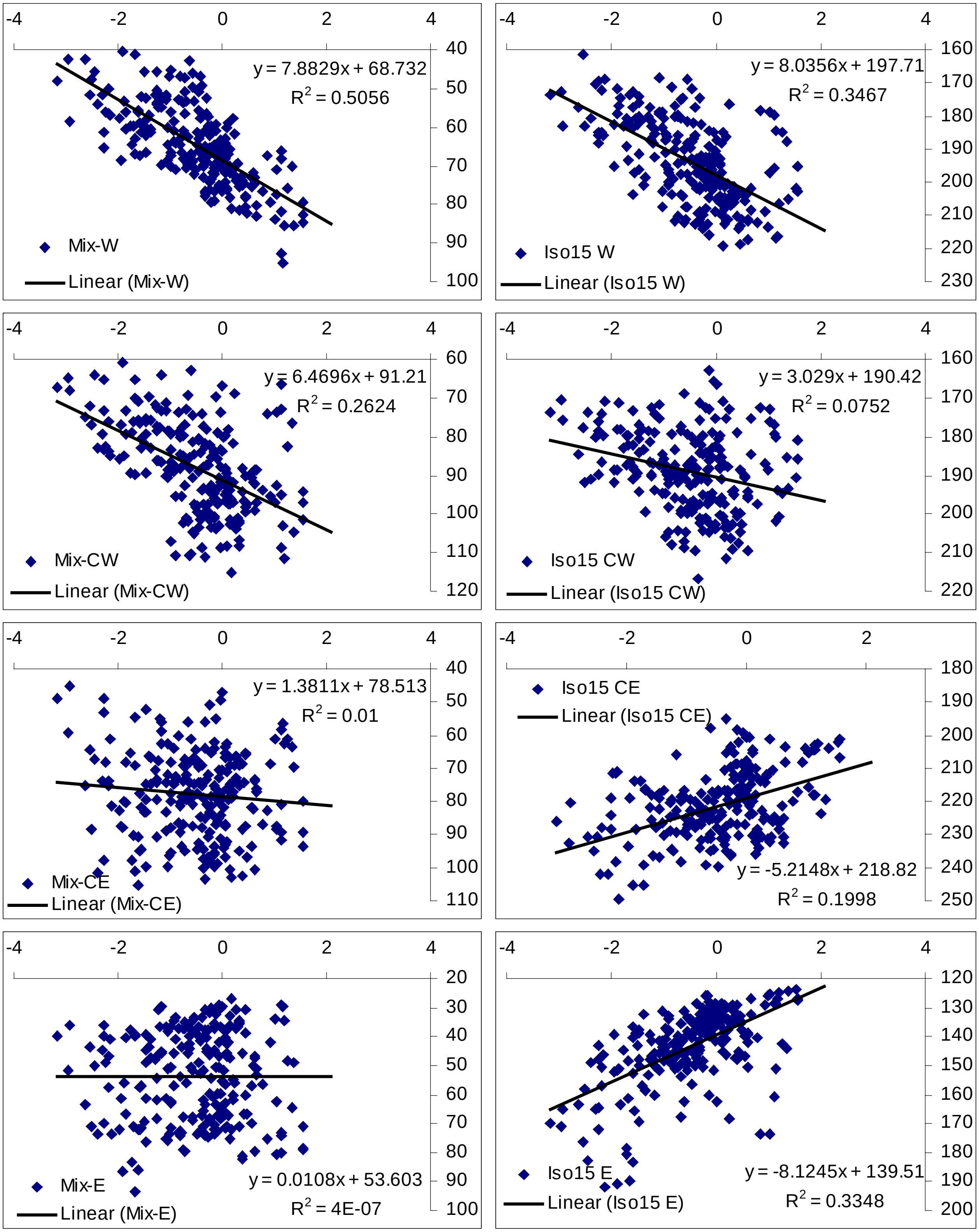


Figure 9. Relations between SOI (abscissa) and depth (m) of mixed-layer (right) and 15oC isotherm (left) in the four geographical boxes, W (120^{o}E-165^{o}E, 10^{o}N-10^{o}S), CW (165^{o}E-150^{o}W, 10^{o}N-10^{o}S), E (150^{o}W-115^{o}W, 0^{o}N-20^{o}S), and CE (115^{o}W-80^{o}W, 0^{o}N-20^{o}S)

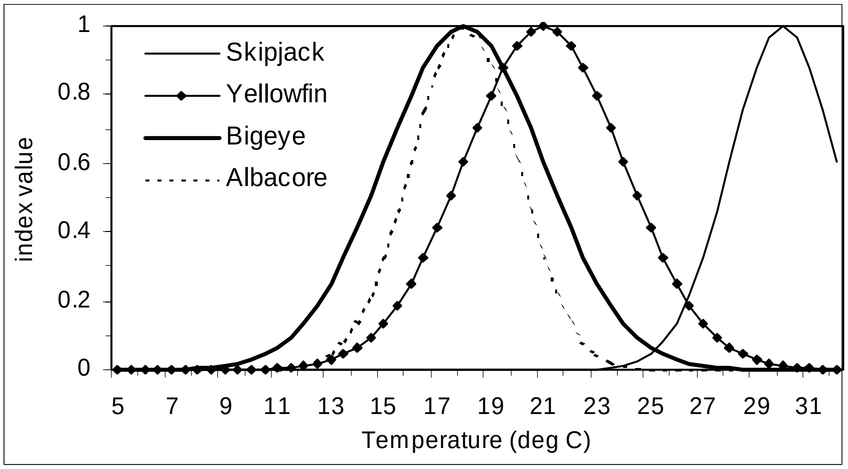


Figure 10. Temperature functions of adult skipjack, yellowfin, bigeye and albacore tuna used for defining the temperature habitat

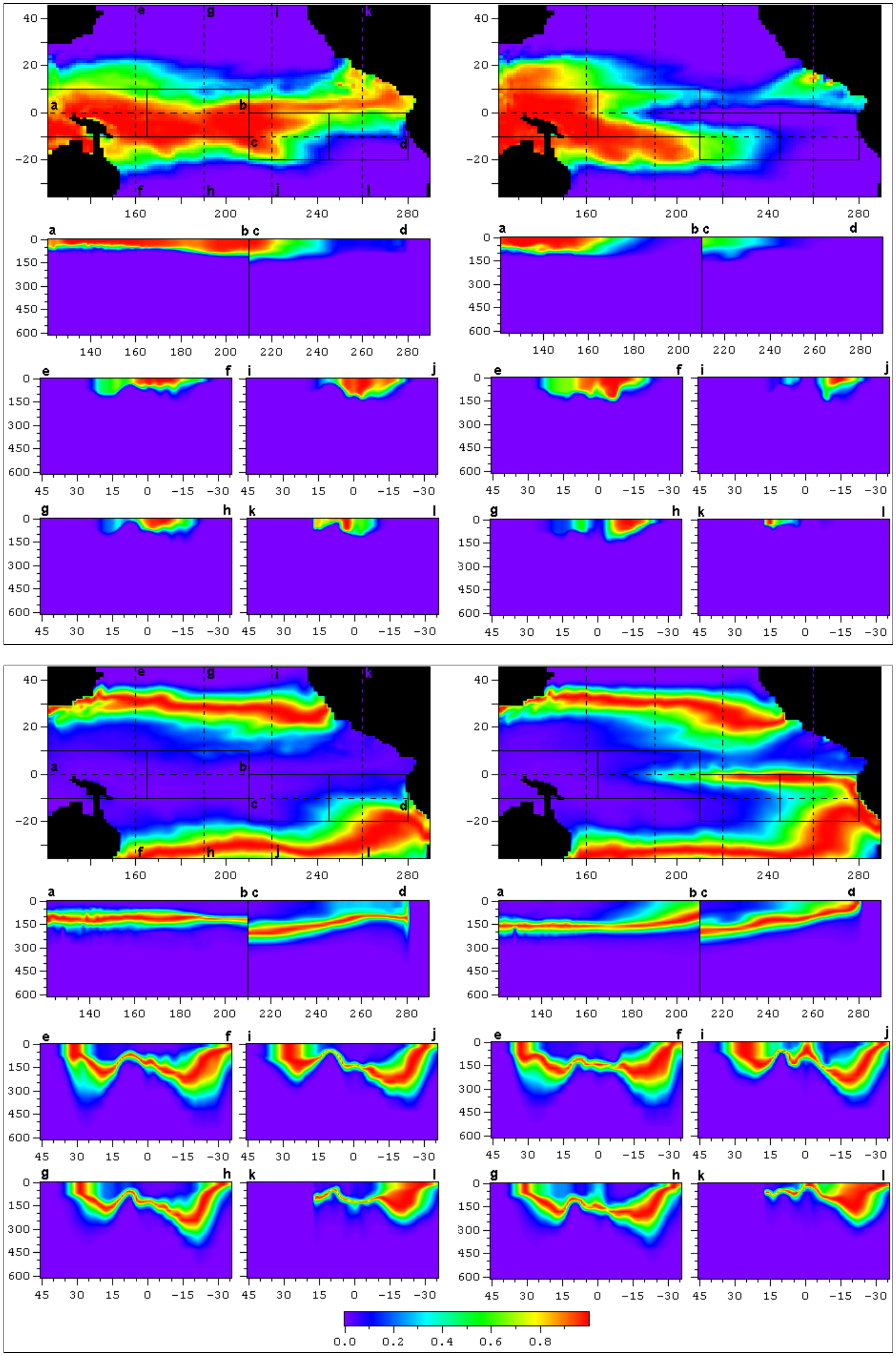


Figure 11. Skipjack (top) and yellowfin (bottom) temperature habitat in December of El Niño and La Niña years

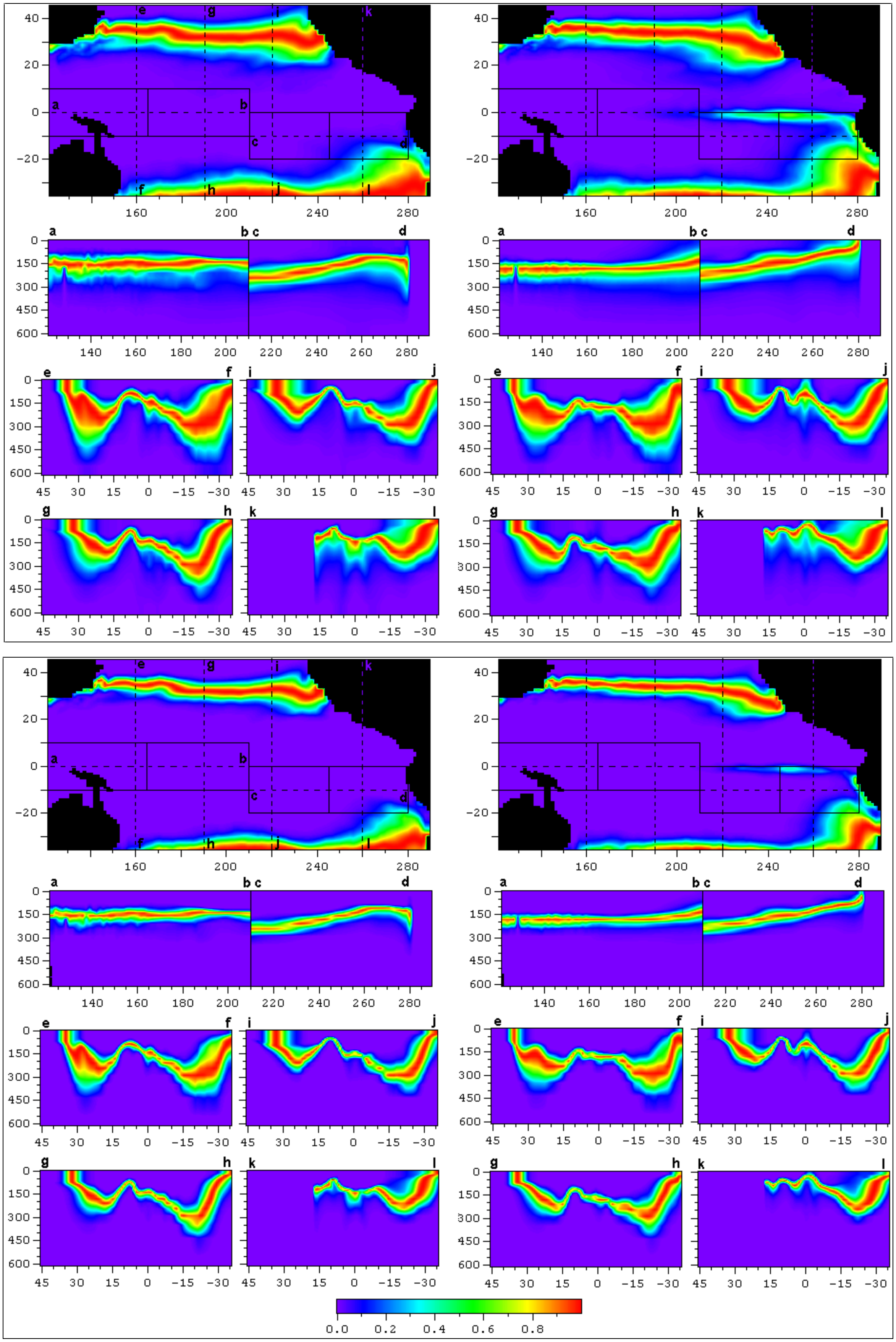


Fig. 11 (cont.). Bigeye (top) and albacore (bottom) temperature habitat in Dec. of El Niño and La Niña years.

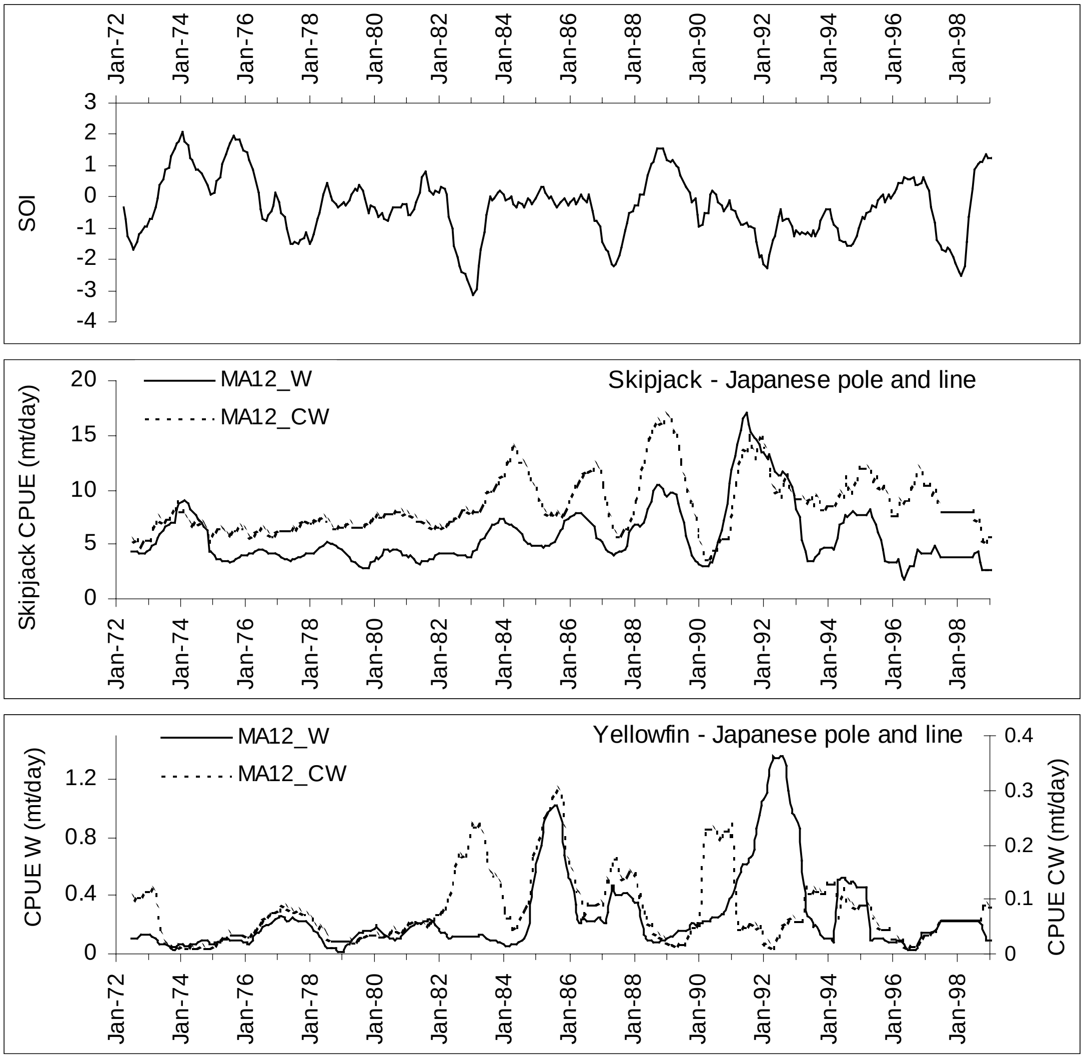


Figure 12. Time series of SOI and Japanese pole and line CPUE for skipjack and yellowfin in the four geographical boxes, W (120°E-165°E, 10°N-10°S), CW (165°E-150°W, 10°N-10°S), E (150°W-115°W, 0°N-20°S), and CE (115°W-80°W, 0°N-20°S). (MA12 = moving average over 12 months).

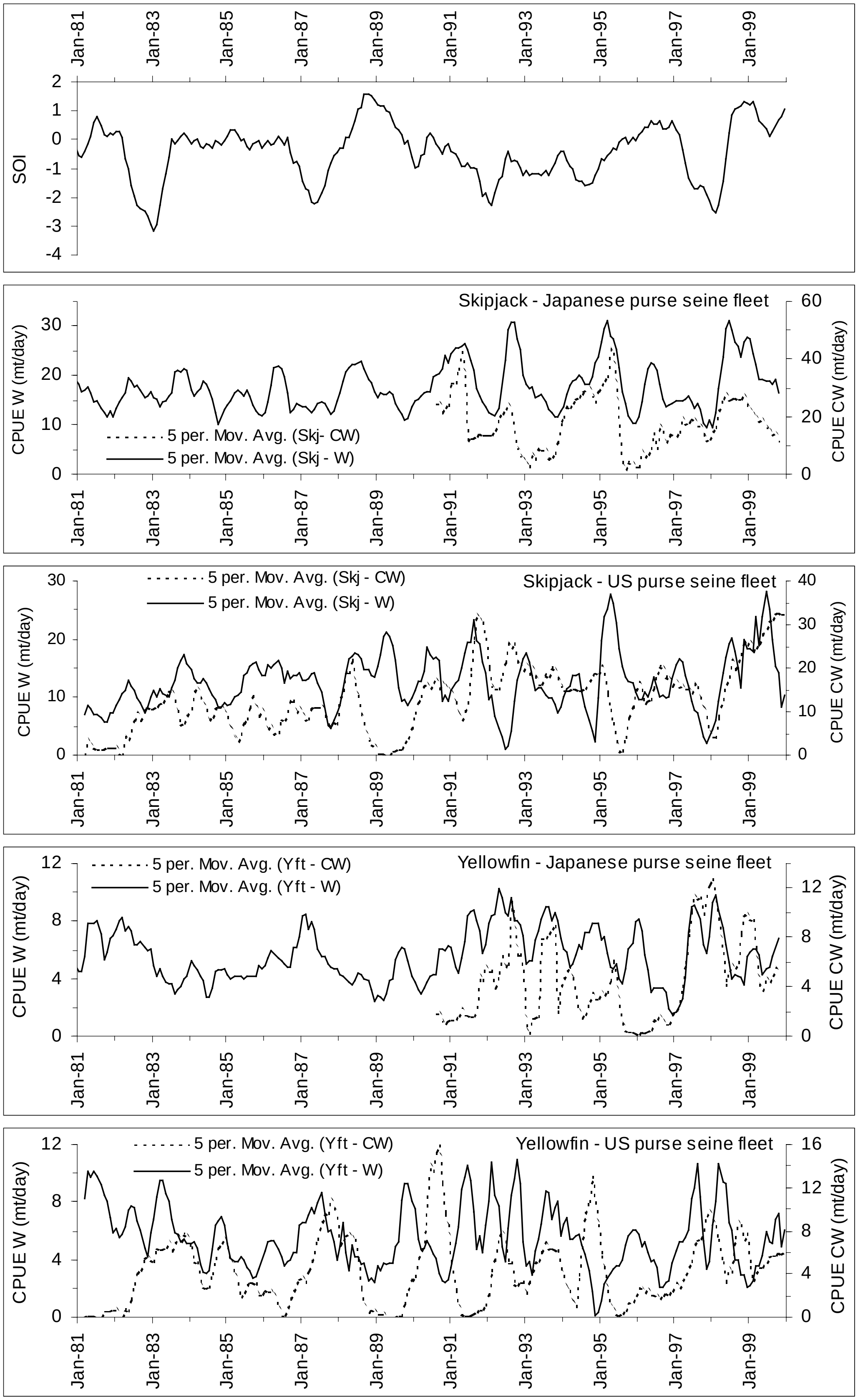


Figure 13. Time series of SOI and Japanese and US purse seine CPUE for skipjack and yellowfin

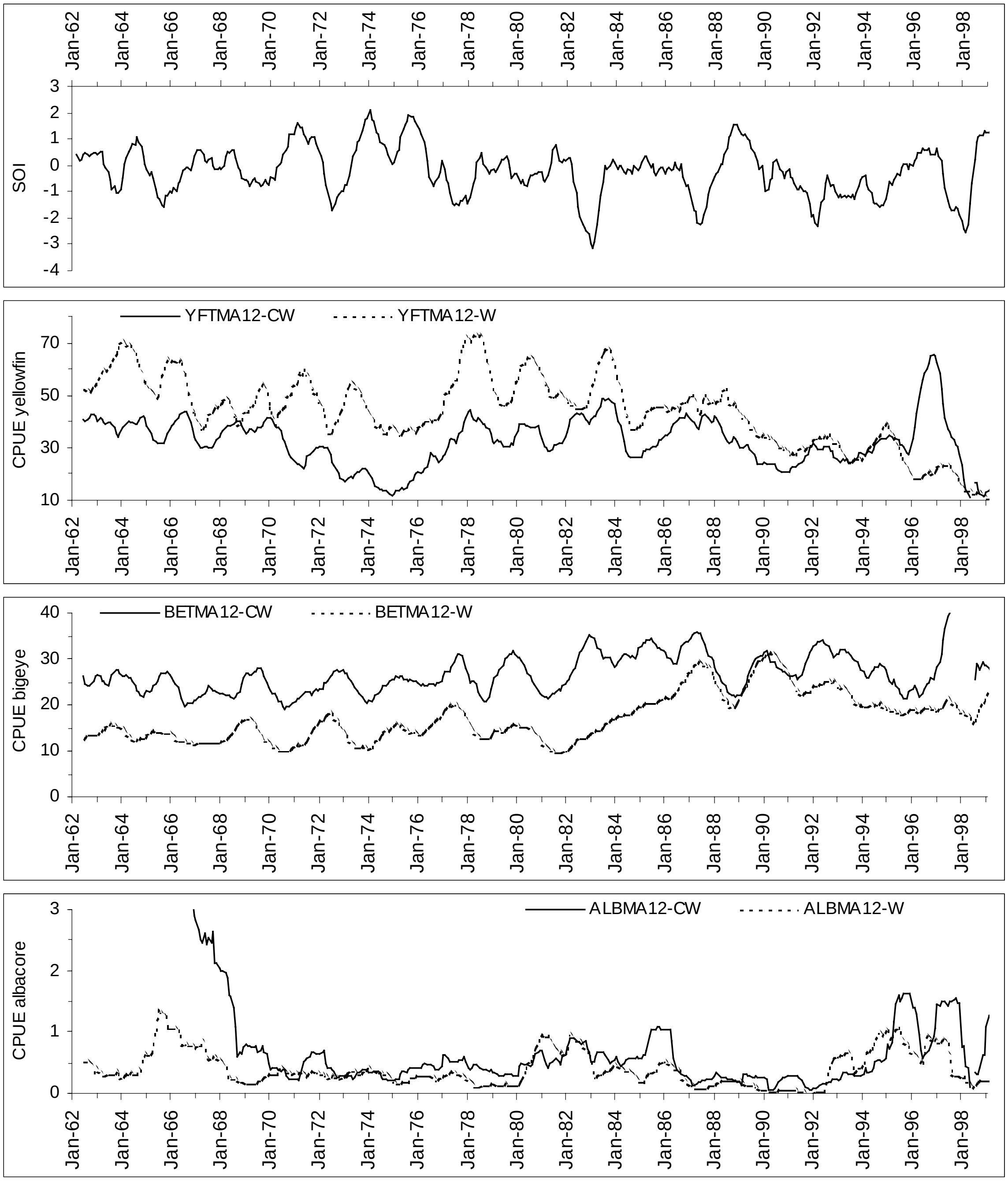


Figure 14. Time series of SOI and Japanese longline CPUE for yellowfin (YFT), bigeye (BET) and albacore (ALB) in the western and central western geographical areas

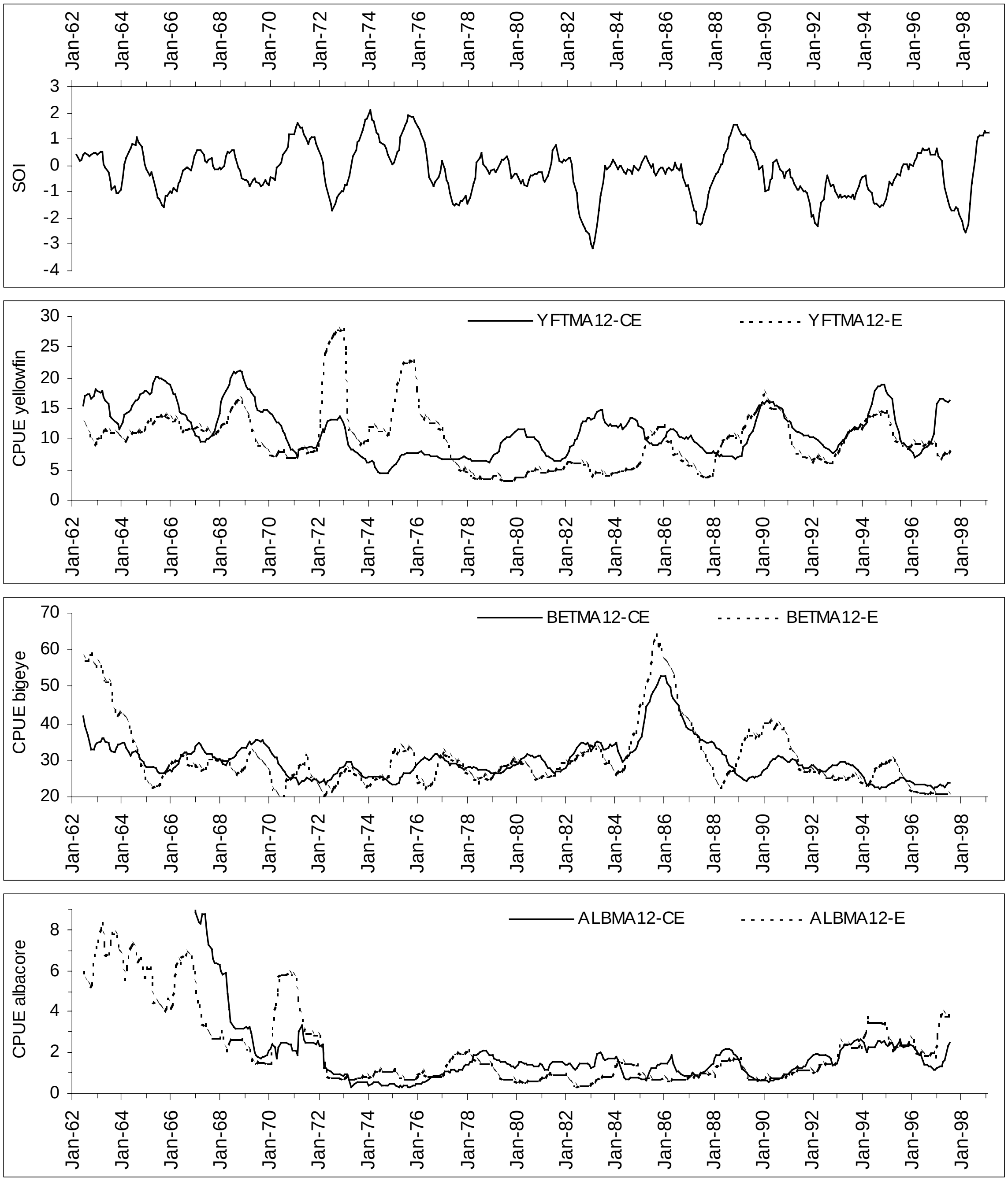


Figure 14 (cont.). Time series of SOI and Japanese longline CPUE for yellowfin, bigeye and albacore in the eastern and central eastern geographical areas

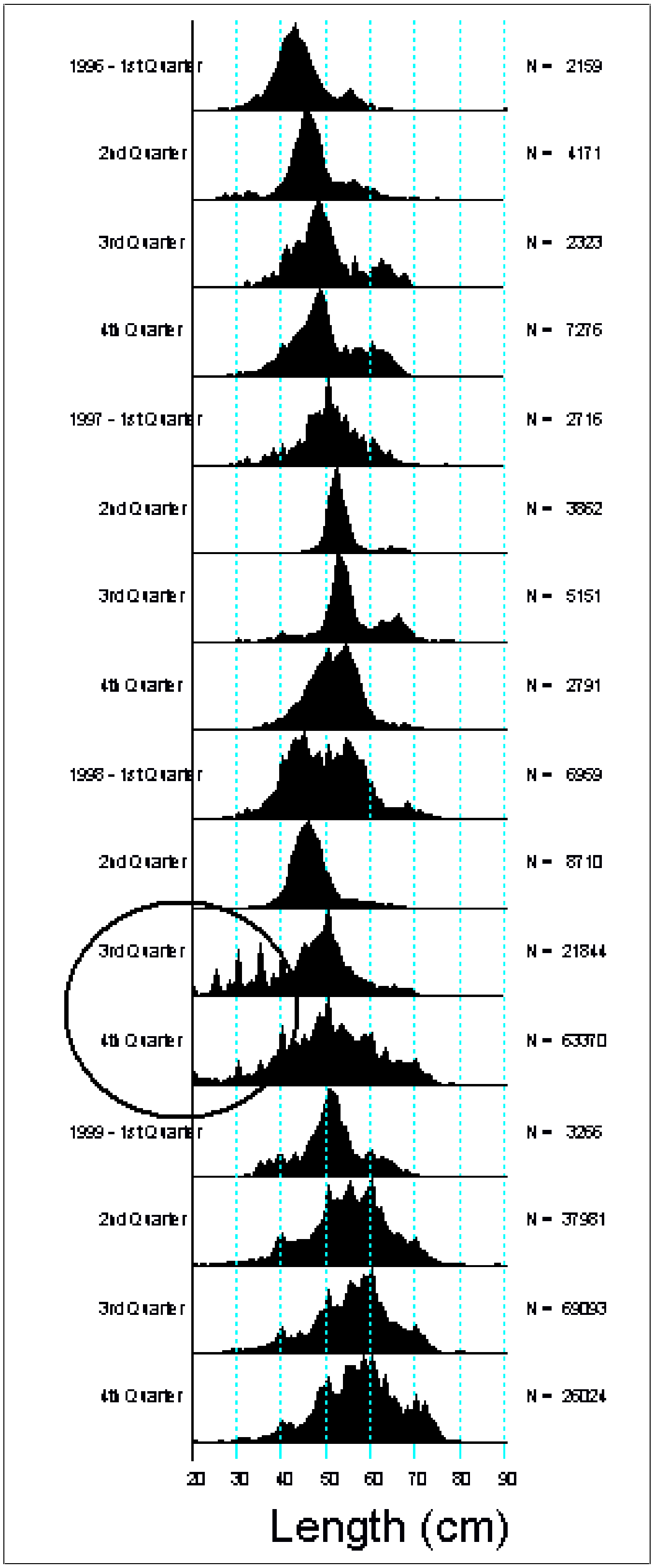
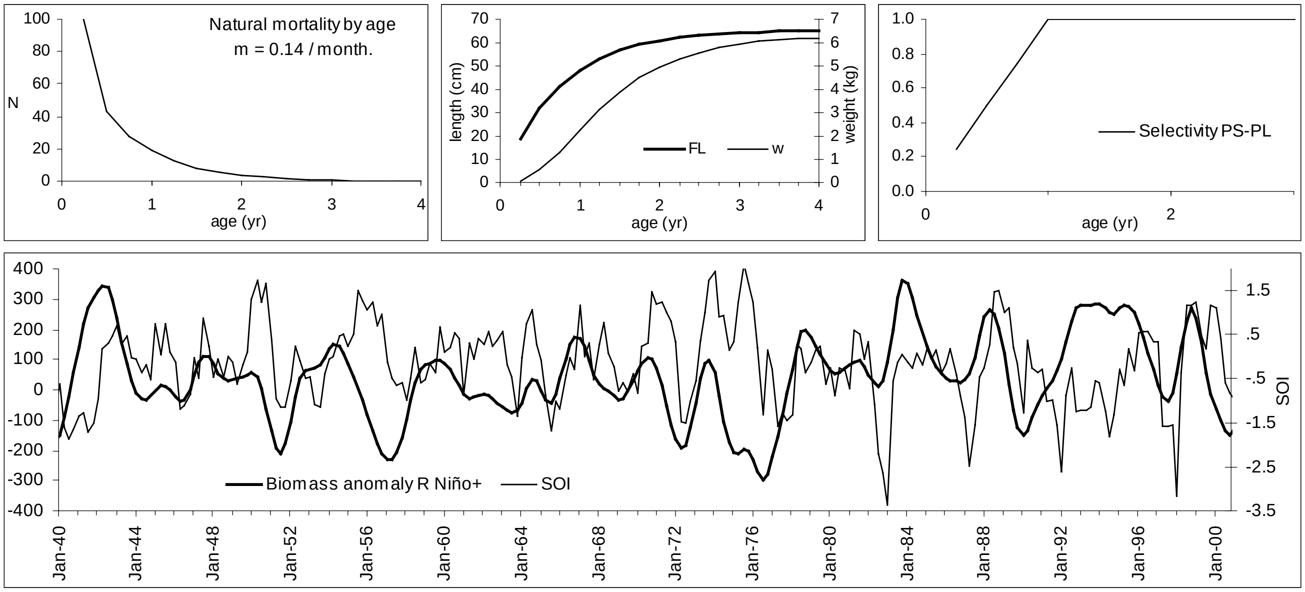


Figure 15. Skipjack length frequencies from regional port sampling data of purse seine catch in the Western and Central Pacific Ocean (WCPO)

Skipjack



Albacore

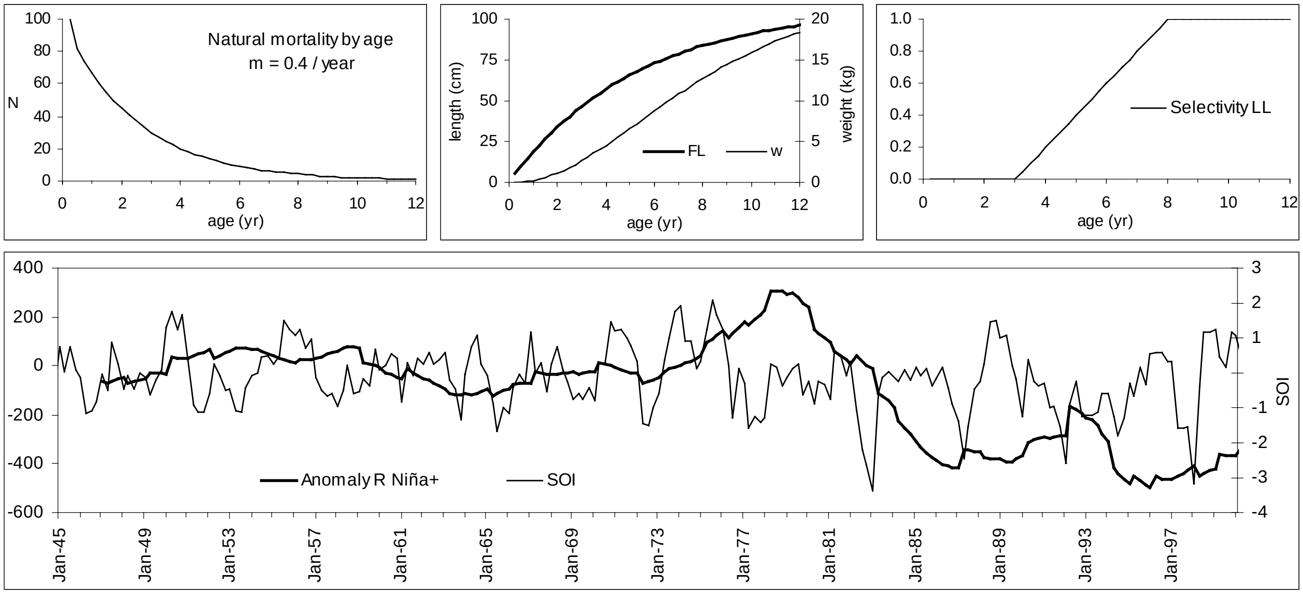
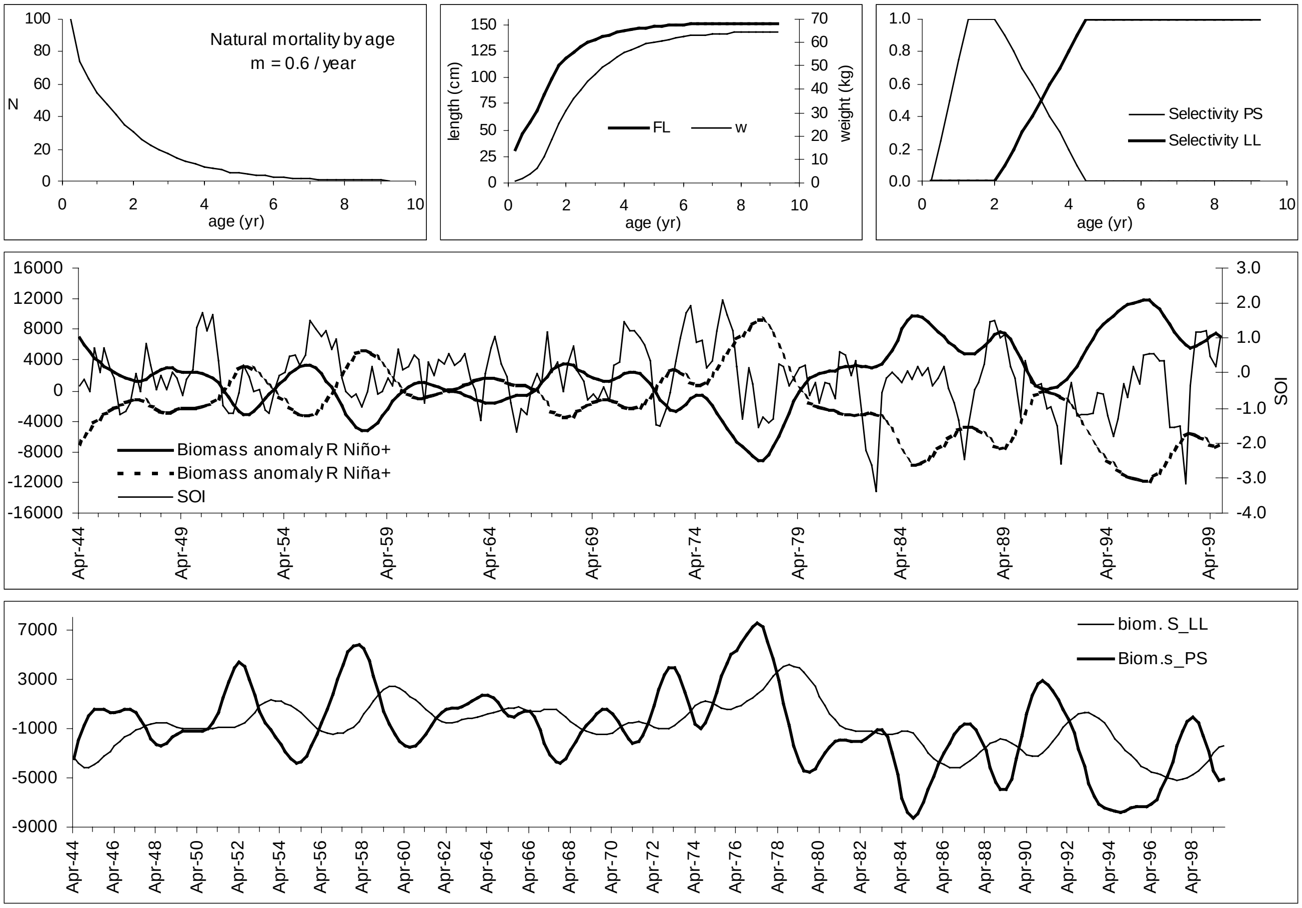


Figure 16. Predicted stock biomass anomaly obtained with a simple population model based on the mortality and growth functions presented on the figure and a recruitment porportional to SOI with a positive effect of El Niño (negative values of SOI) for skipjack, and a positive effect of La Niña (positive values of SOI) for south Pacific albacore.

Yellowfin



Bigeye

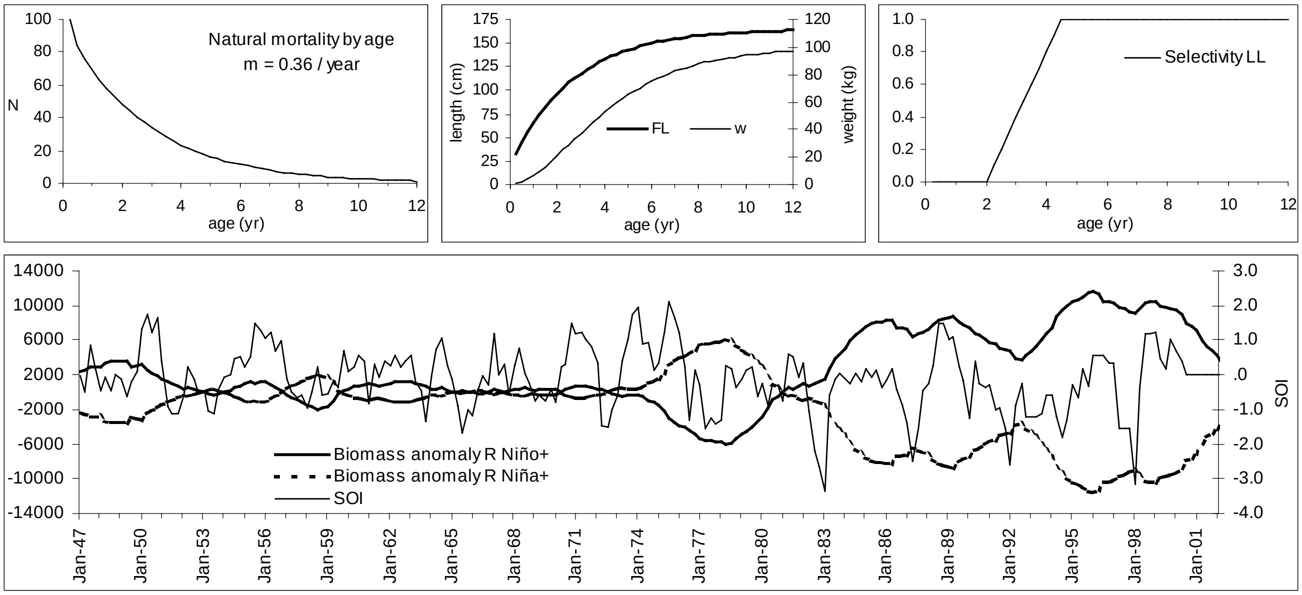


Figure 16 (Cont.). Predicted stock biomass anomaly obtained for yellowfin and bigeye with a simple population model based on the mortality and growth functions presented on the figure and a recruitment porportional to SOI. Both cases of positive effect of El Niño (negative values of SOI) or La Niña (positive values of SOI) are presented. The effect of the gear selectivity between longline and purse seine is illustrated for yellowfin.

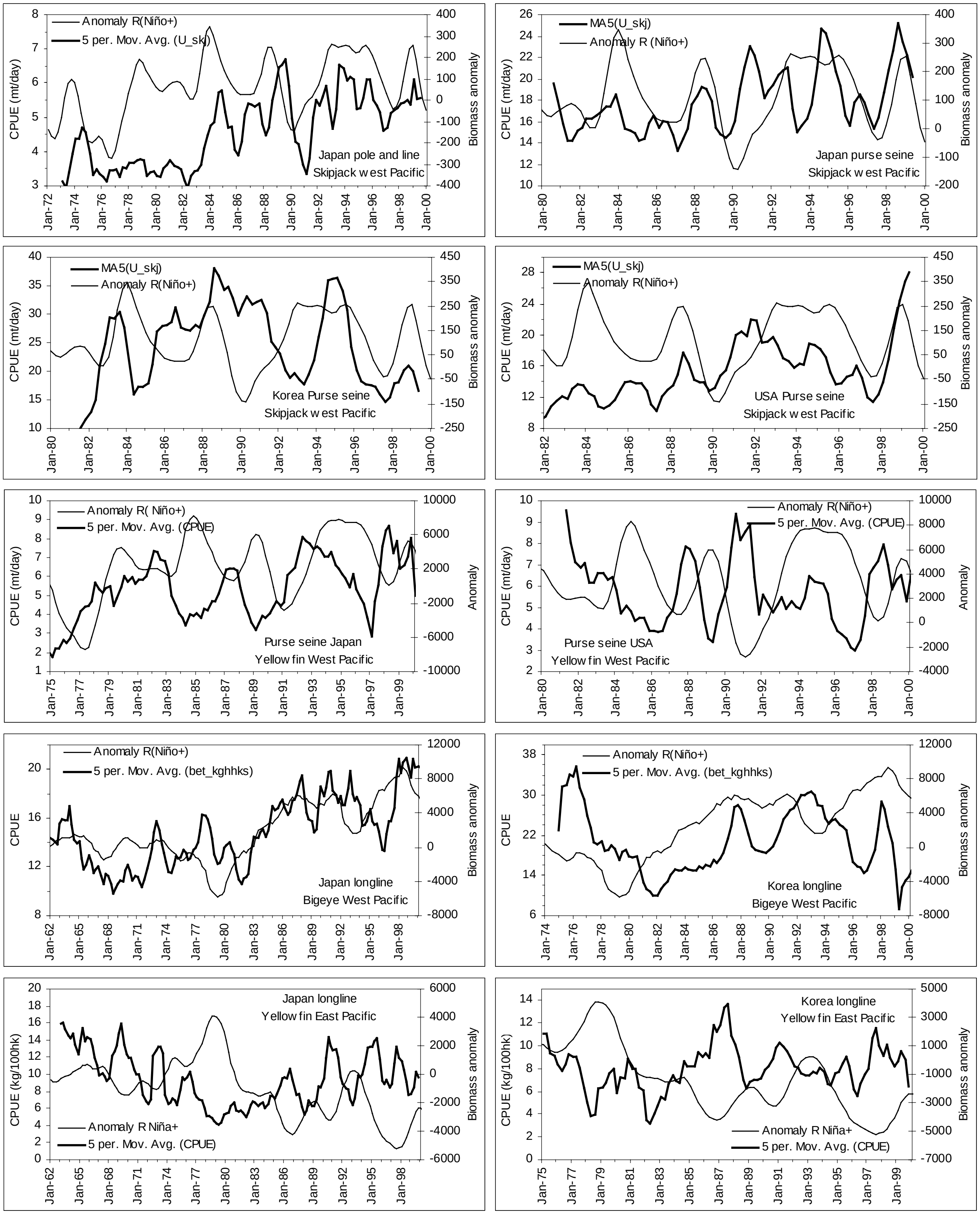


Figure 17. Comparisons between CPUE time serie of different tuna fisheries and the predicted stock biomass anomaly obtained with a recruitment proportional to SOI (see Figure 16).

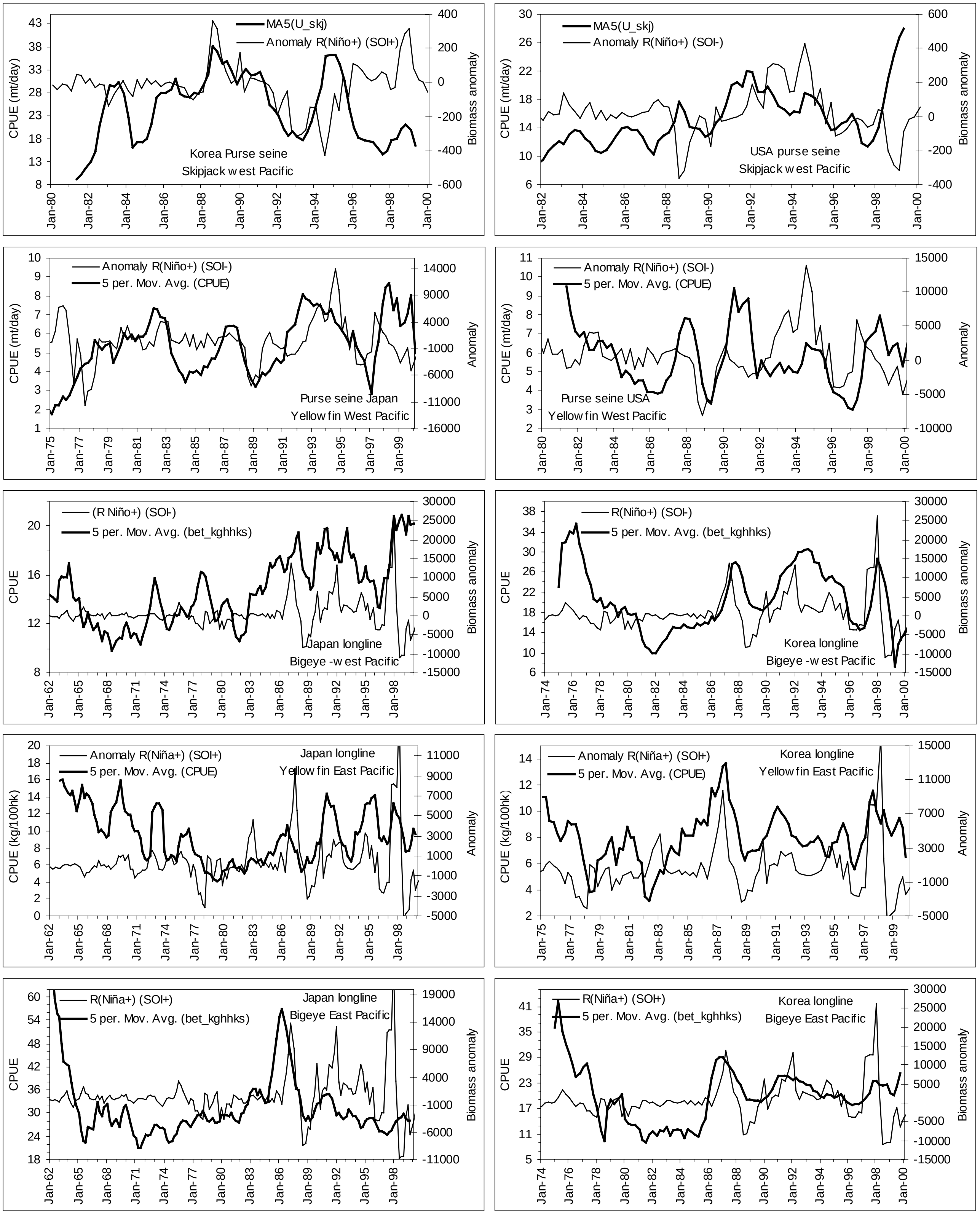


Figure 18. Comparisons between CPUE time serie of different tuna fisheries and the predicted stock biomass anomaly obtained with a recruitment proportional to SOI combined with a direct effect of ENSO (SOI- = positive effect of El Niño or negative effect of La Niña; SOI+ = negative effect of El Niño or positive effect of La Niña).