Climate-induced variation in the distribution, catch and biology of skipjack tuna (*Katsuwonus pelamis*) in the Western and Central Pacific Ocean

기후변동에 따른 중서부태평양의 가다랑어(*Katsuwonus pelamis*)의 변동

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ABSTRACT

Skipjack tuna (*Katsuwonus pelamis*) are the most productive species among the tuna species. The highest skipjack catches are occurred in the Western and Central Pacific ocean, about 830,000 metric tones in 2003. However, although the skipjack catch is very large, the research on skipjack is relatively limited. This work presents how the ocean climate, especially ENSO event, affects on the skipjack tuna in the Western and Central Pacific Ocean. Using Korean purse seine fisheries data, the effect of atmospheric and oceanic fluctuation (the SOI and SST in the NINO3.4 and the main fishing area) on the distribution, catch and biology of skipjack was investigated. From 1985 to 2003, catch and fishing effort data were obtained from the National Fisheries Research and Development

Institute (NFRDI) to provide an index of distribution of skipjack. Biological information (length, weight, gonad weight, etc) of skipjack has been collected monthly from 1994 to 2003. The Secretariat of the Pacific Community (SPC) provided an intensive collection of length-frequency data, and mean length was calculated in monthly basis. The SOI and SST in two considerable areas (i.e., NINO3.4 and the main fishing area) were compared with fisheries and biological information of skipjack to check the presence of delayed interaction between abiotic and biotic factors.

The spatial shift in fishing area occurred with the fluctuation of SOI and SST in two areas. Moreover the negative SOI (El Niño) preceded the eastward movement of G by two to three month period. The catch was more closely related to the SST in the main fishing area than SOI or SST in NINO3.4. However, analysis of the relationship between the SOI and the catch showed that El Niño had a positive affect on skipjack catch, and the change in the SOI preceded the catch fluctuation by about 7 months. The El Niño event had a negative effect on GSI and mean length of skipjack when a biological lag was considered. In addition, when I examined the SPC length frequency data, the regime-specific growth pattern at each discrete period seemed to be related with ENSO. Overall, ENSO appeared to affect not only on the distribution but also on biological condition of skipjack with time lags.

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INTRODUCTION

1. Distribution of skipjack tuna in the Pacific Ocean

Skipjack tuna (*Katsuwonus pelamis*) are commonly found within the 15℃ or warmer isotherm in surface layers of tropical and subtropical waters throughout the world oceans (Matsumoto *et al.*, 1984). They are most abundant in the Pacific Ocean. In the eastern Pacific skipjack populations occur along the west coast of the America, from 34°N off southern California to 27°S off northern Chile (Williams, 1970). However, the largest catch of skipjack occurs in the lower latitudes of the Western and Central Pacific Ocean (WCPO) where warm (SST > 29°C) water masses consistently occur. This area is the world's warmest ocean and is called the 'warm pool.' Due to the pole-ward displacement of warm surface waters along the Asian coast, skipjack have sometimes been captured as far north as 44°N off Japan, and as far south as 37°S off Australia (Forsbergh, 1980).

Skipjack lack swim bladders so a minimum swimming speed is required to maintain hydrostatic equilibrium. Also, they need a minimum dissolved oxygen (DO) level of about 2.45 ml/l to maintain a basal swimming velocity. A higher DO level, of about 3.0-3.5 ml/l, would be required for better survival over extended periods (Sharp, 1978).

The vertical distribution of skipjack is limited by the temperature and DO concentrations. A high DO concentration is essential to generate metabolic heat, so both temperature and DO concentration are important factors that determine the vertical distribution of skipjack. Usually in surface waters the concentration of DO is about 4.5 ml/l, but below the thermocline it often is less than the minimum requirement (Toole *et al.*, 1988). Therefore, the properties of the thermocline restrict the vertical distribution of skipjack. Large skipjack need to stay in the vicinity of cooler water to regulate their excessive metabolic heat. Large skipjack (> 6.5 kg) need to stay in the vicinity of cooler water to regulate their high metabolic heat so they usually reside in the vicinity of the thermocline, adjacent to cooler water - as low as 20℃. In contrast, small skipjack (< 4 kg) reside in warmer (30℃ or more) surface waters (Barkley *et al.,* 1978).

2. Biological characteristics of skipjack tuna

2.1 Feeding and growth

Juvenile skipjack are mainly piscivorous although they take various prey organisms (Tanabe, 2001). Adult skipjack also feed mainly upon fishes, but are known to feed on crustaceans, and mollusks. Cannibalism is common. Generally their diet composition is broad, so skipjack are considered to be opportunistic feeders.

Several reports comment on age determination of skipjack (Radtke, 1983; Uchiyama and Struhsaker, 1981; Wild *et al.*, 1995; and Tanabe *et al.*, 2003), but there is no general agreement about best ageing techniques. In comparisons among laboratories, results varied among different methods and scientists. Usually, vertebrae, dorsal spines or otoliths were used to estimate the fish age. Among these, otolith increment counts appeared to show the most reliable results. Wild *et al.* (1995) studied the periodicity of increment deposition in otolith of adult skipjack tuna and found a deposition rate of 0.7 increments per day. A recent study by Tanabe *et al.* (2003) concluded that increments were formed daily in juvenile skipjack otoliths and these increments had a width range of 15-40 µm. In particular, growth of the marginal increment progressed from morning to evening and was completed during the night.

Without reliable age determination of skipjack, the predicted sizes-at-age estimates cannot be determined with certainty. Sibert *et al.* (1983) found that there were significant differences in the parameters of the von Bertalanffy equation estimated from the same regions at different times. The value of the parameter K of the von Bertalanffy growth equation for skipjack varied among different regions around the Pacific Ocean (from 0.11 to 2.00, Wild and Hampton, 1994)

2.2 Maturation and spawning

Sexual maturity seems to be completed at around 40 cm length and first spawning may occur between 40-45 cm, or larger (Matsumoto *et al.*, 1984). Fecundity varies both with oceanic region and fish size. For example, 50 cm skipjack in the eastern Atlantic produced nearly equal number (300×10^3) of ova as 60 cm skipjack in the Pacific (Batts, 1972, Joseph, 1963). However, 70 cm skipjack in the Pacific had a higher fecundity (970×10^3) (Joseph, 1963) than skipjack in the Atlantic (600×10^3) (Batts, 1972). In both areas, however, fecundity ranged between 80,000 to 2,000,000 eggs and large females produced significantly more eggs than smaller females (Wild and Hampton, 1994).

From gonadal studies in the Pacific, Atlantic and the Indian Ocean, Matsumoto *et al.* (1984) found that skipjack spawn year-round near the equator and from spring to fall in subtropical waters. In an earlier study in the Indian Ocean, Stequert and Ramcharrun (1996) found that spawning activity occurred throughout the year. In this study, I examined maturity stages of gonads and found the 70 percent of females had ovaries in the terminal stage of maturation.

2.3 Movement and migration

In general, most tuna species are highly migratory but skipjack seem to have a relatively limited degree of movement. Two tagging experiments were conducted in the Western and Central Pacific Ocean: from October 1977 to August 1983 by the Skipjack Survey and Assessment Programme (SSAP), and from July 1989 to December 1995 by the Regional Tuna Tagging Project (RTTP), In both tagging experiments, the median displacement of skipjack was 28 and 158 nautical miles, respectively (Sibert and Hampton, 2003). Similarly, in other oceans (Indian and Atlantic Oceans), most tagged skipjack were found within 1500 nautical miles during several month. The conclusion of these observations is that skipjack populations probably are quite "viscous" (MacCall, 1990).

3. Abundance and fisheries of skipjack tuna in the Pacific Ocean

3.1 Fisheries in Western and Central Pacific Ocean

Skipjack make up the largest part of the catch among tuna and tuna-like species, contributing about 55% of total (Fig. 1). In the Pacific Ocean, the catches, (i.e., distribution and abundance) of skipjack has changed in time between two different regions: the eastern Pacific Ocean (EPO), and the

Western and Central Pacific Ocean (WCPO) (Fig. 2). The division of two sections occurs at 150°W. Skipjack catches in the WCPO have increased steadily since 1970, and stabilized during the late 1990s and early 2000s, at about 1,100,000 metric tones (mt). The increase in 1980s was due to the growth in the international purse-seine fleet, combined with increased catches by domestic fleets from the Philippines and Indonesia. Also, in the 1980s canneries did not buy tuna caught in contravention of the dolphin protection regulation. This resulted in the relocation of many purse seiners from the EPO to the WCPO.

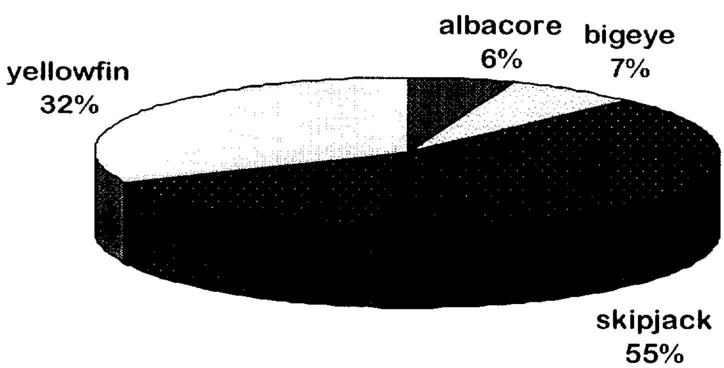

Fig. 1. Components of the main tuna species caught in the Pacific Ocean in 2003.

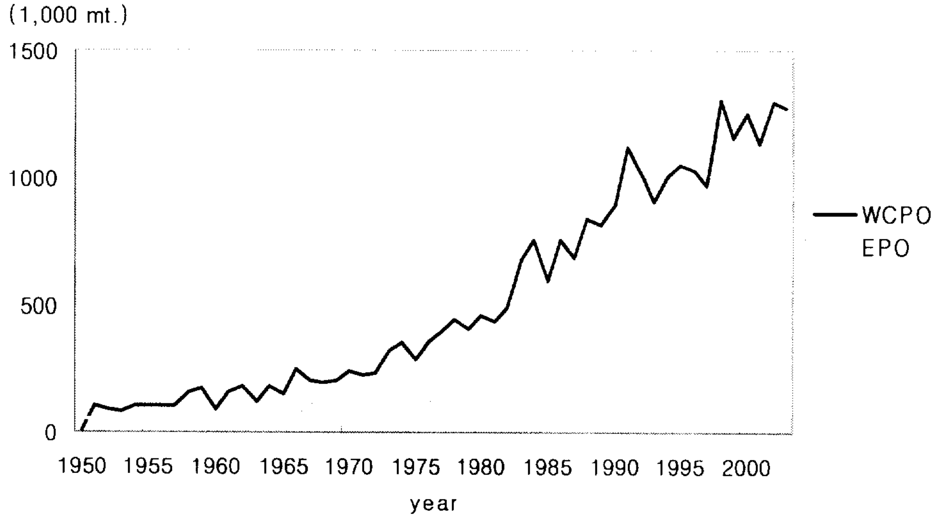

Fig. 2. Skipjack tuna catch in the Western and Central Pacific Ocean and Eastern Pacific Ocean from 1950 to 2003.

3.2 Korean fisheries

Korea is one of the major tuna-fishing countries operating in the WCPO area, along with Japan, Taiwan, USA, and Papua New Guinea. Korean fleets started to operate in the WCPO in the 1980 and 1981 seasons when large-scale purse seining was introduced to this area. Along with the increase in the number of fishing vessels, the fishing areas were expanded. In 2003, the Korea catch was about 18% of the total skipjack catch in the WCPO 153,328 mt of a total of 823,849 mt (Fig. 3). Fluctuations of two catches, examined by correlation analysis, are highly significant ($R=0.901^{**}$, $p>0.01$).

The net used by most Korean purse seine vessels is about 2.4-3.5 km long and 270-300 m deep (An, 2001). Skipjack reside in the vicinity of the thermocline. The depth of thermocline depth in the WCPO is from 50 m during El Niño to 300 m during La Niña (An, 2001). Therefore the net can reach the bottom of skipjack schools at all times.

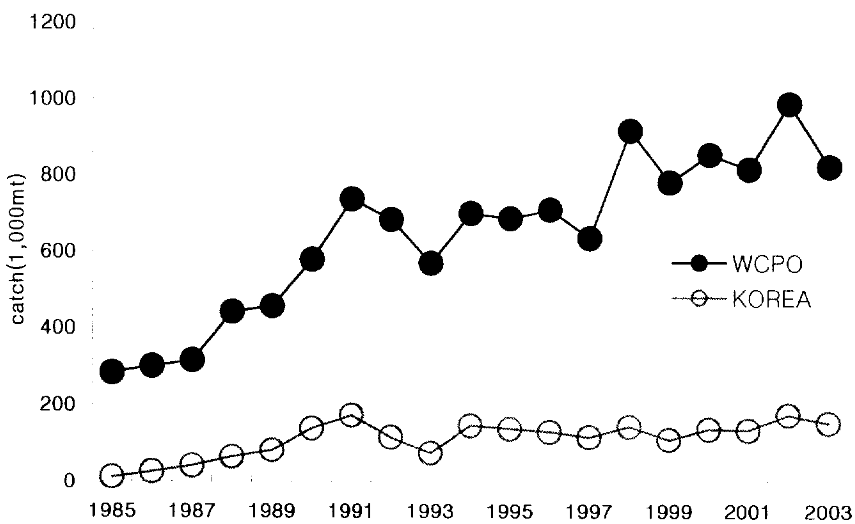

Fig. 3. Annual skipjack tuna catch by purse seine in the WCPO (closed circle) and Korean (open circle) fisheries during 1985-2003 (data from Secretariat of the Pacific Community and Korean Deep Sea Fisheries Association).

4. Oceanic environments and skipjack tuna

4.1 Climate and oceanic environments

The climate of the Pacific Ocean is not stable and appears to fluctuate between different regimes. Usually one climate regime continues for several years or decades, then changes. During such a change, oceanic environments such as seawater temperature, salinity and productivity are modified in the new regimes. There are two major indicators of change in oceanic conditions: the Pacific Decadal Oscillation index (PDO) and the Southern Oscillation Index (SOI) (Fig. 4). The PDO is concerned with inter-decadal change, but the SOI is related to inter-annual variation (Mantua *et al.*, 1997). The PDO is the first component of EOF (Empirical Orthogonal Function) analysis for the North Pacific SST. The SOI is a principal mode of surface atmospheric pressure between the Australian-East Asia region and the eastern tropical Pacific.

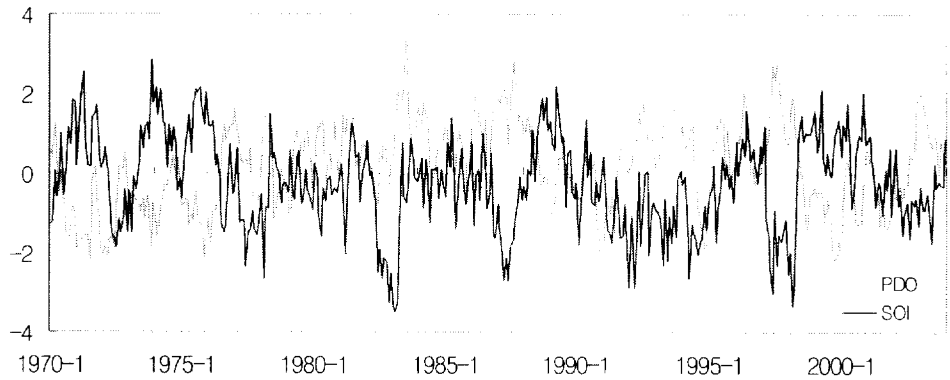

Fig. 4. Fluctuations of PDO and SOI from 1970 to 2002 data from Joint Institute for the Study of the Atmosphere and Ocean (JISAO) and Climatic Research Unit.

In the equatorial Pacific, warm and relatively less saline surface waters pile up in the western Pacific by westward trade winds, and form the "warm pool" (Fig. 5). The warm pool is a region characterized by low a primary productivity rate (Longhurst *et al.*, 1995) and is subject to a strong east-west movement on interannual time scales in accordance with the SOI fluctuation (Picaut *et al.*, 1996). In particular, the region from 5°S to 5°N, 170°W to 120°W (NINO3.4) has a highly variable SST over El Niño time scales, and the SST in NINO3.4 area has a strong negative correlation with the SOI (Barnston and Chelliah, 1997).

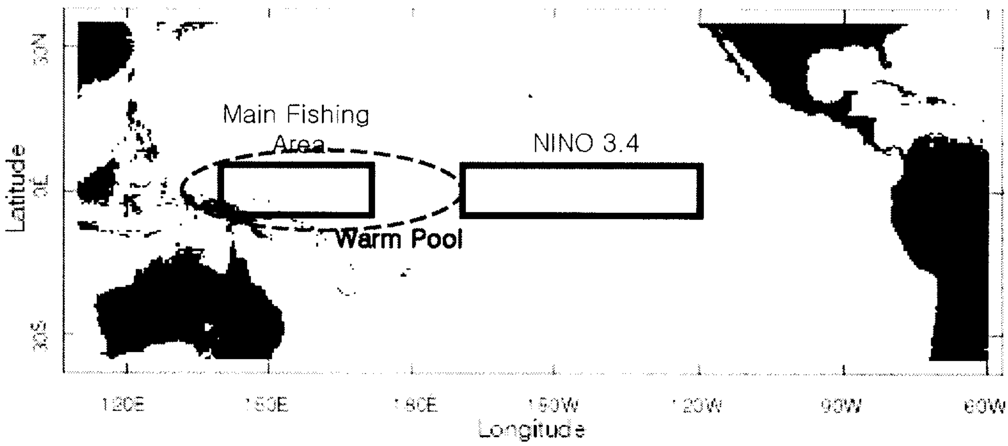

Fig. 5. Locations of main fishing areas: rectangles show the main fishing area of Korean fleet (140°E-170°E, 5°N~5°S) and the NINO3.4 (170°W-120°W, 5°N~5°S). The dashed line indicates the location of the Warm Pool.

4.2 Relationship between environments and fish

Climate variation can impact the environment of fish and therefore affect its behavior such as migration, reproduction activity, adaptation to environment change (Le Blanc, 1997). Compared with the impact of climate change variation on lower trophic levels (Brodeur and Ware, 1992, Sugimoto and Tadokoro, 1997, Francis *et al.*, 1998), climate change impacts on higher tropic levels are more varied (Hollowed and Wooster, 1995). Previous studies indicate that the distribution of skipjack is affected by El Niño-Southern Oscillation (ENSO), the main factor causing atmospheric change in tropical Pacific. The relationship between the distribution of skipjack and the warm pool was discussed by Lehodey *et al.* (1997). Analysis of catch and effort data from the US purse seine fisheries in the western Pacific demonstrated that most successful fishing grounds were in the vicinity of a convergence zone between the warm pool and the equatorial upwelling area in the central Pacific. The east-west shifts in fishing vessel locations and the convergence zone coincided according to ENSO events.

Using a coupled dynamical bio-geochemical model, Lehodey *et al.* (1998) predicted the distribution of skipjack tuna forage that is believed to be a major factor in explaining the zonal distribution of the fish stock. The convergence zone of the horizontal currents, which corresponded to the warm pool/equatorial upwelling boundary, has the close relationship with the displacements of skipjack. The predicted enrichment in forage appeared the inner edge of the warm pool where currents converge. The high catch rates corresponded closely with the area of maxim forage.

Skipjack recruitment, estimated from a statistical population dynamics model (MULTIFAN-CL) was compared with climate indices during the last five decades (Lehodey *et al.*, 2003). There is a negative correlation between the SOI and PDO. During the positive PDO phase, a higher frequency of El Niño occurs while La Niña events are more frequent during the negative phase of PDO. When the PDO shows a positive phase and high frequency of El Niño events occurs, an apparently positive impact occurs on recruitment of skipjack.

Global warming causes significant change of skipjack habitat in the equatorial Pacific (Loukos *et al.*, 2003). The warming simulation is controlled by the atmospheric CO_2 concentration. The simulation shows an increase of skipjack forage on the equator and in the east, and a reduction on north and south side of the equator. However, favorable skipjack habitat extended widely over the tropical ocean by the surface warming of oceanic waters.

5. Purposes of the research

Skipjack catches are highest in the western central equatorial Pacific where several fishing nations, including Korea, have operated since the middle of 20th century. However, although the skipjack catch is very large, the research on skipjack is relatively small. Because this area is the dominant area of the warm pool, ENSO events affects conditions there. Lehodey *et al.* (1997) discussed the spatial shift of skipjack tuna population related on ENSO in the WCPO, but the impacts of ENSO events on the biological condition of skipjack have not been considered. The National Fisheries Research and Development Institute (NFRDI) of Korea has collected biological information on skipjack since late 1993. Catches of Korean fishing vessels in the WCPO made up about 18% of total skipjack catches at the area.

The basic objective of this study is to use Korean fisheries data to investigate how ENSO events affect the zonal extension of skipjack in the WCPO. A complementary objective is to examine the relationship between these changes in ocean climate and skipjack biological factors such as growth and maturation related and ENSO variability. Also, the temporal anomaly in mean length data from commercial catch data was examined relative to ENSO events to investigate the effect on the size of fish.

MATERIALS AND METHODS

1. Environmental data

1.1 Southern Oscillation Index (SOI)

The SOI, as an index of ENSO, was obtained on a monthly basis from the Climate Research Unit, University of East Anglia, UK (http://www.cru.uea.ac.uk/ 17 August 2004). The SOI anomaly is calculated as the variability in surface pressure anomalies between Tahiti in the Central Pacific (17°37'S, 149°27'W) and Darwin, Australia (12°25'S, 130°51'E), using the method of Ropelewski and Jones (1987). To compare and correlate with data on fisheries and biological characteristics of skipjack tuna, data on the SOI anomaly were selected during January 1985 - December 2003.

1.2 Sea Surface Temperature (SST)

The SST data were obtained from the Climate Diagnostics Center (CDC, http://www.cdc.noaa.gov/cgi-bin/PublicData/getpage.pl) on a monthly basis (January 1985 to December 2003) for two areas: NINO3.4 (5°N~5°S, 170°W-

120°W) and the main fishing area of Korean purse seiners in the WCPO (MAFA, 5°S-5°N, 140°E-170°E) (Fig. 5).

2. Fisheries information

Although the skipjack catch by Korean purse seine fishery made up only about 20% of the total WCPO catch, the total WCPO and Korean catches were highly correlated, and the temporal fluctuation patterns were similar (Fig. 3). Both data sets show that catches were increased dramatically from 1985 to 1991, then decreased until 1993. During the non-El Niño period the catch seemed to be stable from 1994 to 1996. The fishery data from the WCPO shows that catches were elevated since 1998, the recent biggest El Niño. Catches were also higher in 2002, another El Niño year.

Catch and fishing effort data were obtained to provide an index of distribution of skipjack. Korean purse seiners operating in the Pacific Ocean have reported catch and effort data to the NFRDI since 1980. The time-longitude section of monthly skipjack catch (in tonnes) and effort (in fishing days in the month) was calculated in the area 5°N-5°S, 120°E-150°W from 1985 to 2003 by months and 1° of longitude. The longitudinal gravity centre of CPUE in month j (G_j) was calculated with the equation below (Lehodey *et al.*, 1997). Catch data collected since 1997 were not complete so fishery data from 1997 to 2003 were not chosen to calculate the correlation coefficients.

$G_j = \sum_i L_i(C_{ij}/E_{ij})/\sum_i(C_{ij}/E_{ij})$ ---------------------------- (1)

L_i: the longitudinal mid-point of the i^{th} area of 1° longitude between 5° N and 5° S.

C_{ji}: the skipjack catch in area *i* in month *j*

E_{ji}: the number of fishing days in area *i* in month *j*

3. Biological data

Since 1994, biological information of skipjack has been collected in every month at the tuna canning factory in Chanwon, Korea. About 200-300 skipjacks caught in the WCPO were weighted, measured in folk length, and identified by sex. The weights of the gonads were measured from about 40-60 skipjacks, and Gonadal-Somatic Index (GSI) was calculated by each sex as below.

$GSI = gw/bw * 100$ ---------------------------- (2)

gw : gonad weight

bw : body weight (include gonad)

From 1994 to 2003, monthly mean length and GSI were calculated to delineate growth pattern and maturation process with time.

The Standing Committee on Tuna and Billfish (SCTB) of the Secretariat of the Pacific Community (SPC) maintains an intensive collection of length-frequency data, collected from 21 ports in 10 countries in SPC. The sampling method of SCTB requires that five fish are selected at random from every net. From 1988 to 2003, the sample range of 733-46,697 was collected in every month. Monthly mean length was calculated from the data sets transferred by the SCTB as below.

$$M_j = \sum(L_i+0.5)N_{ij}/\sum N_{ij} \qquad \text{----------------------------- (3)}$$

M_j : mean length in month j

L_i : length range i

N_{ij} : no. of fish in length range i in month j

4. Analytical methods

The correlations of environmental data on fisheries and biological factors were examined using SPSS software. Time lags of 0 to 12 months were used to examine cross-correlation function (CCF) and check the presence of delayed interaction between environmental, fisheries and biological data of skipjack.

RESULTS

1. Influence of environmental variability on skipjack fisheries

Interannual changes in the SOI and SST in NINO3.4 matched inversely with a strong interannual changes in the eastward expansion of the western equatorial Pacific warm pool. For example, during El Niño events (i.e., low SOI period) in 1986/87, 1991/92, and 1997/98, the SSTs in NINO3.4 were highest (Fig. 6a). When ENSO indicators (i.e., SOI and SST in NINO3.4) displayed large interannual variations, the SST in the MAFA (5°S-5°N, 140°E-170°E) fluctuated within a small range, about 1-2°C, and it appeared to vary in the opposite direction to the SST in NINO3.4 (Fig. 6a). During recent significant El Niño event from late 1997 to early 1998, the SOI changed from positive to negative and SST in NINO3.4 changed in the opposite direction (Fig. 6a).

The pattern of interannual change in G (the computed longitudinal gravity center of the CPUE) closely tracked SOI variability (Fig. 6b). For example, during the 1986/87 El Niño event, the location of fisheries shifted to the east, and then moved to the west during La Niña period of 1988/89. Further, two other El Niño events in 1990's (1991/92, 1997/98) demonstrated a similar shift in the distribution pattern fishing vessel locations. During the recent El Niño of 2002/03, there was an extreme movement in G to the east. Statistically significant correlations between G and ENSO indicators were found (Table 1). In particular, G was significantly correlated with the SOI and SST in NINO3.4 ($r=0.647^{**}$ and $r=0.489^{**}$, respectively). On the other hand, G was negatively correlated ($r=-0.228^{**}$) with the SST in the MAFA.

Skipjack catches in the Korean fishery (Fig. 6b) fluctuate substantially. In particular, catches were significantly higher in 1991 and 1995, but dropped suddenly in 1992 and 1996. In contrast to changes in G, there were no significant correlations between skipjack catch and ENSO indicators. However catch was significantly correlated ($r=0.304^{**}$) with SST in the MAFA (Table 1).

The El Niño had dynamic impacts on skipjack fisheries in tropical ecosystems. The cross-correlation analysis, with time-lags, indicates that the SOI and SST in NINO3.4 were maximal with no time-lag (not shown here). However, the cross-correlation coefficient between G and SOI was negative and greatest with a time lag two or three months. The SOI preceded the eastward movement of G by two and three months ($r=-0.699^{**}$) (Fig. 7). Also cross-correlation between the SOI and the skipjack catch was statistically significant with 5-7 month time-lag (Fig. 7).

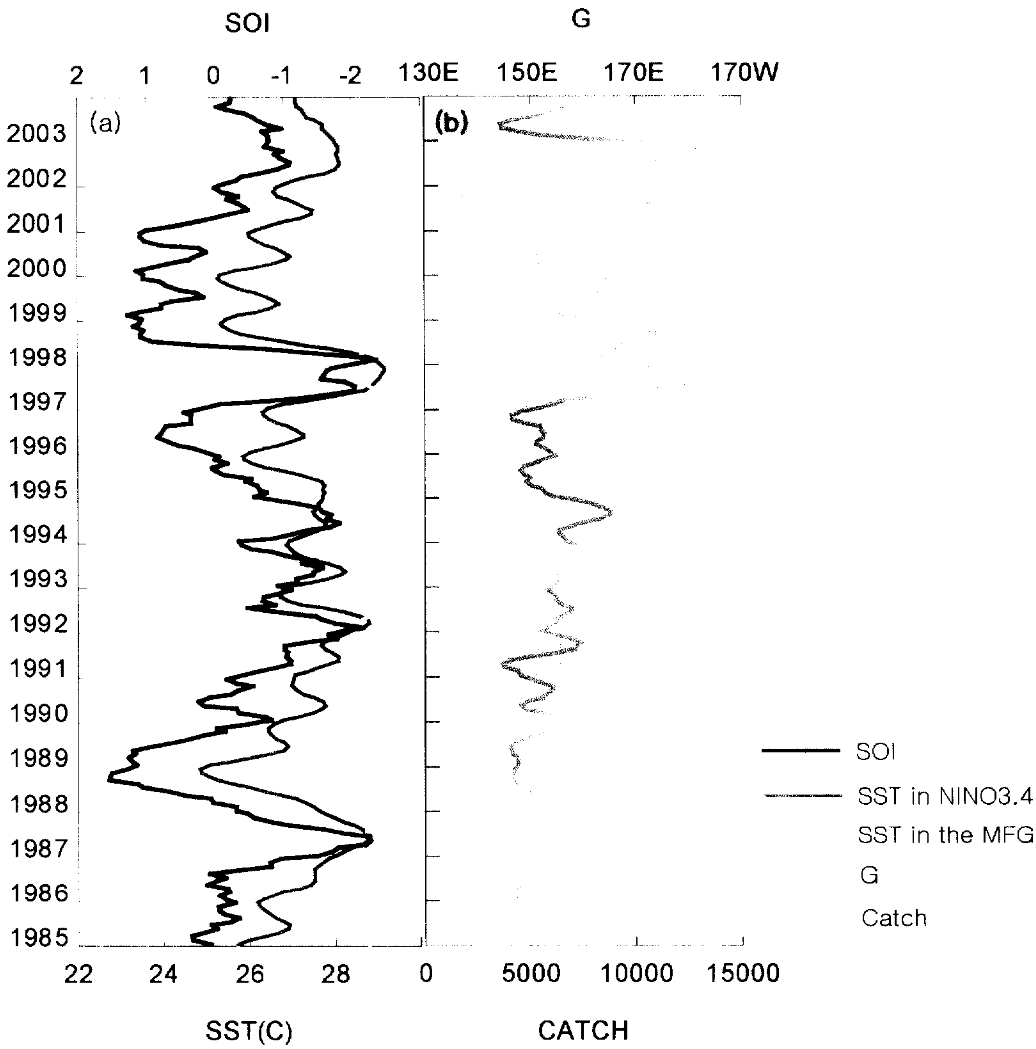

Fig. 6. Monthly fluctuation of fisheries and environmental parameters during 1985-2003. (a) SOI, SST in main fishing area and NINO3.4, and (b) longitudinal gravity centre of fishing ground (G) and catch of skipjack tuna; each factor was smoothed with a five month moving average.

Table 1. Correlation coefficients between environmental indices and fisheries factors during 1985-1996.

	G (n=140)	CATCH (n=140)
SOI	-0.647**	-0.108
SST in NINO3.4	0.489**	0.120
SST in Main fishing area	-0.228**	0.304**

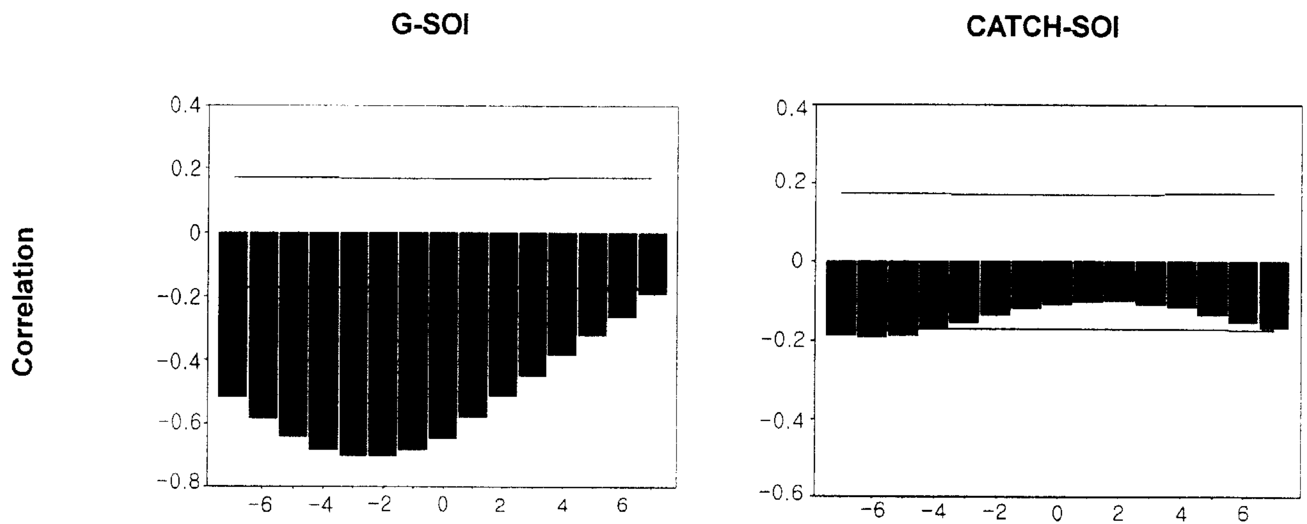

Fig. 7. Cross-correlation with a time-lag (in month) during 1985-1996.

2. Influence of environmental variability on skipjack biology

The time-series information on fork length and GSI from the Korean purse seiners varied with time (Fig. 8). Although biological characteristics fluctuated with time, there was no seasonality in growth and maturation (Fig. 8b). Instead, variation in mean length and GSI seem to respond to ENSO events. After the intense ENSO in 1997/98, there was a pronounced decrease in mean length. In contrast, mean length increased and continued through the duration of during La Niña in 1998/99. During the last half of 2001 to the first half of 2002, considered to be an El Niño period, the mean length of skipjack decreased.

The male and female GSI also changed with time, coincident with changes in length. The patterns of change matched the SOI except in 1994/95 (Fig. 8b). In particular, during the 1997/98 El Niño event, the GSI increased, reached a peak. Subsequent low SOIs after 1999 roughly matched the relatively higher levels of GSI concurrently.

Table 2 shows significant correlations between ENSO indicators and biological parameters. When the SOI was low or the SST in NINO3.4 was high (i.e., El Niño year), skipjack length was small ($r=0.272^{**}$) and mean GSIs were high ($r=-0.359^{**}$ and $r=-0.278^{**}$ for male and female, respectively). Though SST in the MAFA did not influence on GSI, it had a significant correlation with length (r=-

0.184^{*}).

The El Niño has a delayed effect on skipjack biology (Fig. 9). The cross-correlation coefficients between the SOI and mean length was positive and greatest with a 5-month time lag (r= 0.474^{**}). Similarly the positive cross-correlation coefficients between SOI and GSI were greatest with a time lag of 8-9 months (r=0.401^{**} and r=0.441^{**} for male and female, respectively). In contrast when no time lag was considered, the correlation coefficients between SOI and GSI was negative.

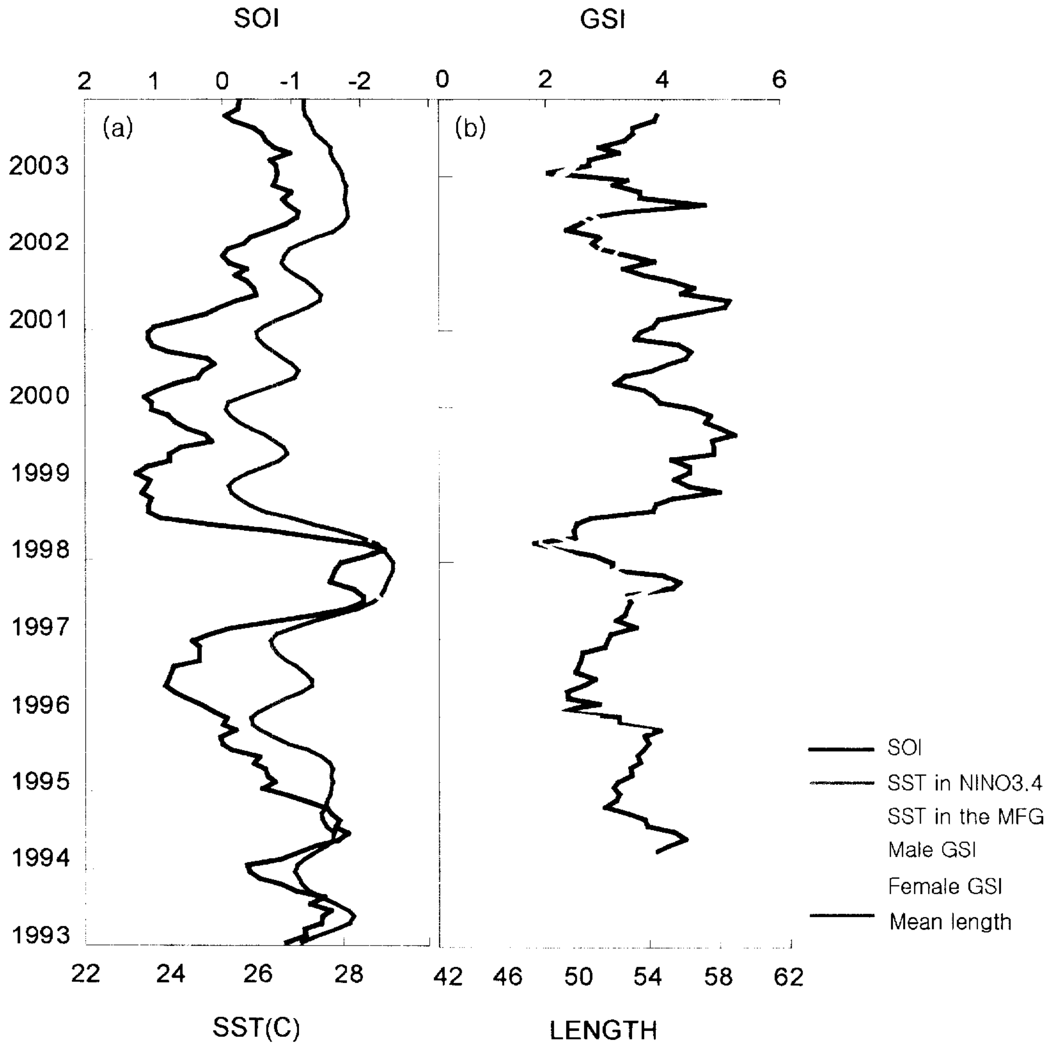

Fig. 8. Monthly fluctuation of (a) SOI, SSTs in main fishing area and NINO3.4, and (b) man length and GSI of male and female. Each factor was smoothed with a five month moving average.

Table 2. Correlation coefficients between environmental indices and biological factors during 1985-1996.

	Mean length (n=120)	GSI-male (n=119)	GSI-female (n=119)
SOI	0.272**	-0.359**	-0.278**
SST in NINO3.4	-0.362**	0.376**	0.266**
SST in Main fishing area	-0.184*	-0.093	-0.047

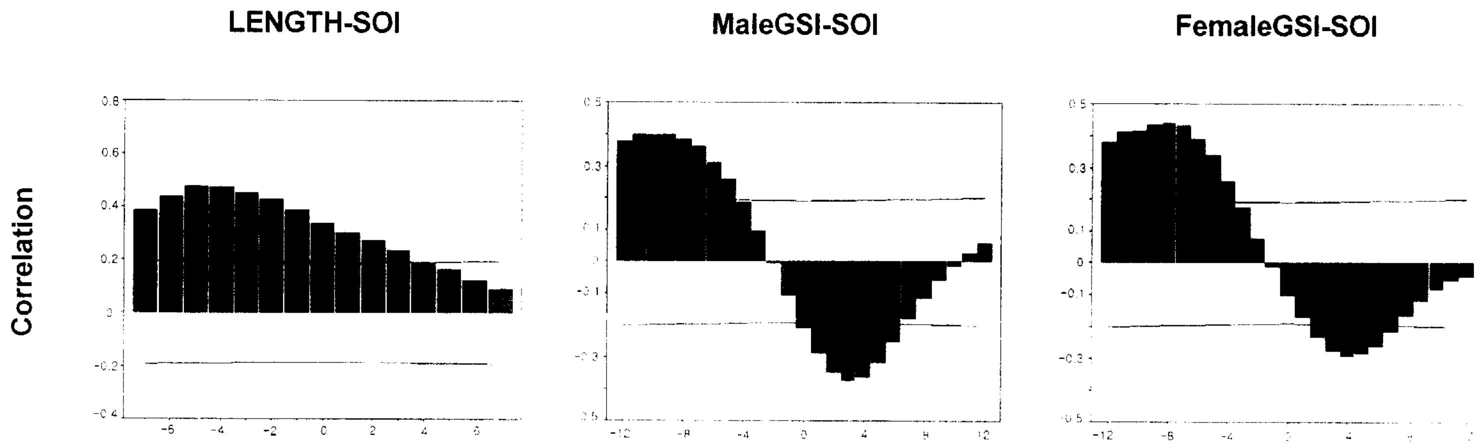

Fig. 9. Cross-correlation with a time-lag (in month) during 1985-1996.

3. Change in mean length with ENSO events

Analysis of the SCTB data sets, that have longer sampling periods than Korean purse seine data, show that there are temporal changes in the mean length of skipjack.

An alternate pattern in size variability appeared. The study period was divided into four different periods according to anomaly patterns: 1988-1992, 1993-1998, 1999-2001, and 2002-2003 with anomalies of 2.32, -1.87, 1.23, and -1.66, respectively. During two of these periods, 1988-1992 and 1999-2001, had a positive anomaly of length, while negative anomalies appeared in the 1993-1998 and 2002-2003 periods.

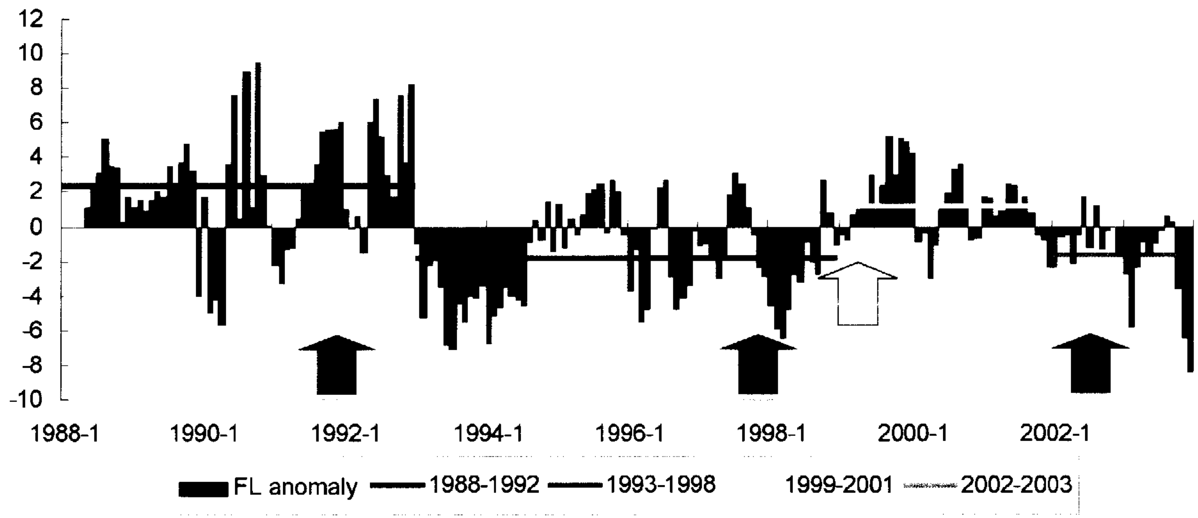

Fig. 10. Anomaly of mean-length caught in the WCPO during 1988-2003: each bar indicates the mean anomaly at each period. Dark arrows indicate El Niño events and light arrow indicate La Niña.

DISCUSSION

1. Shifts of Korean fishing ground

Sea surface temperature data from the NINO3.4 region and SOI were analyzed with Korean fishing data to examine the potential impacts and mechanisms of climate variation on skipjack distribution. The El Niño-Southern Oscillation (ENSO) is an atmospheric-ocean phenomenon that occurs in the tropical Pacific Ocean. Lehodey *et al.* (1997) showed that the east-west movement of skipjack distribution was affected by ENSO events and the geographic shifting in the 29℃ isotherm. This research also revealed the evidence of a strong relationship between ENSO indicators (i.e., SOI and SST in NINO3.4) and skipjack distribution. During El Niño events, fishing grounds are extended eastward relative to non-El Niño periods. These shifts in skipjack distribution can be explained with changes in the location of the fronts between the warm pool and the upwelling cold water. When westwardly-advected cold water from the central-eastern equatorial Pacific encounters sporadic eastwardly-advected warm water from the western equatorial Pacific, the location of convergence zone changes, and this has an important role in determining the location of high abundance of skipjack (Lehodey *et al.*, 1997).

Lehodey suggested that skipjack can support their high energy requirement even when they stay in the oligotrophic warm water because of the large oceanic frontal area and biological convergence. To examine the distribution of primary production and tuna forage, Lehodey *et al.* (1998) used a bio-geochemical model, which showed primary production occurred between the warm pool and equatorial upwelling. The simulated tuna forage accumulated in the convergence zone of the horizontal currents where high catch rates of skipjack occurred.

One of the objectives of this study was to examine Korean purse seine catch data following the approach developed by Lehodey *et al.* (1997). Since the implementation of exclusive economic zones of Pacific Island countries since 1988, fleets of purse seiners including Korean vessels have had restricted fishing opportunities. However, this analysis indicated that the Korean fishing data still showed the influence of ENSO in spite of the limitation of the data.

The effect of SOI on the movement of skipjack was seen best with a two or three months time lag. The delay in the fluctuation of G indicated that, after a change of SOI (an atmospheric condition), the biological response of skipjack (i.e., the movement of skipjack) required some time periods. For example, 2-3 months after an El Niño, the fishing area extended to the east. The SOI affected on the geographic location of Korea and American (USA) fishing locations after two-months time-lag (Lehodey *et al.*, 1997), nevertheless the main fishing locations of two nations were slightly different (Fig. 11) because of other factors such as the distance to offloading sites also may affect the precise distribution of the skipjack fishing fleets of various fishing nations.

The SOI is an atmospheric component of El Niño. However, for better predictions of skipjack fishing grounds, I also consider an oceanic component of El Niño: the SST in NINO3.4. Understanding factors affecting the displacement of skipjack is a prerequisite for better fishing efficiency because the potential skipjack fishing area is extremely wide. If either the SOI or the SST in NINO3.4 can be pre-determined, then locations with high abundance of skipjack might be predicable. Although less important than ENSO events, a lower SST in the main fishing location also shifts fishing locations eastward.

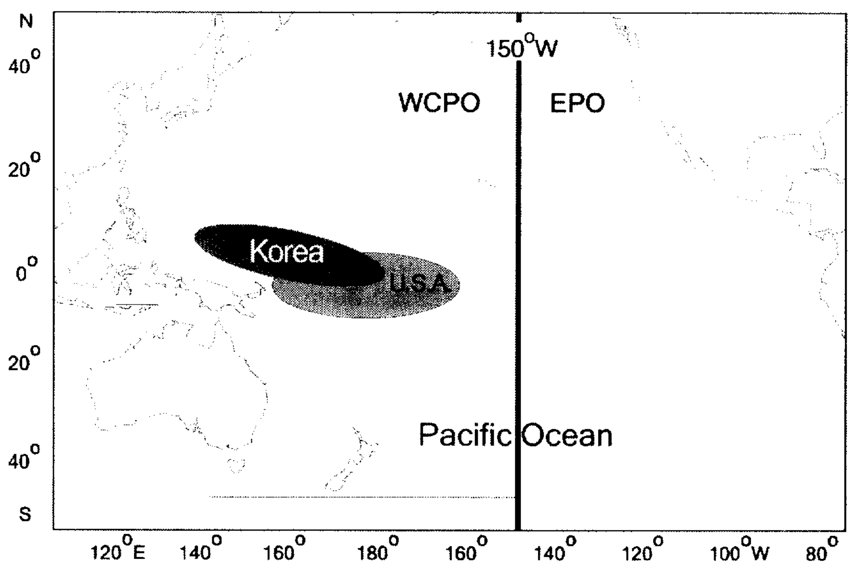

Fig. 11. The boundary of the WCPO and EPO (solid line) and estimation of Korea and USA fishing areas of purse seine fishing in the WCPO (An, 2001).

2. Fluctuation of catch

Given the assumption that catch rates can represent skipjack abundance, the catch in the warm pool seemed to be related more to the SST in the MAFA (5°S-5°N, 140°E-170°E) rather than ENSO factors. With an increase of SST in the MAFA, the catch increased. Analysis of the relationship between SOI and catch showed that El Niño had a positive affect on skipjack catch, and the change (negative correlation) in the SOI preceded the change in catch by about 7 months.

From the recent results of modeling on skipjack, this positive effect from ENSO is predictable. Because of the warm water extension in the Central Pacific and the increase of primary productivity in Western Pacific during El Niño periods, the recruitment of skipjack increased in Western and Central Pacific Ocean (Lehodey *et al.*, 2003). In particular, during the strong El Niño event in 1997/1998, high recruitment was indicated in results from the MULTIFAN-CL model (Hampton, 2002). Also direct observations on skipjack also detected this phenomenon: at the end of 1998, large numbers of juvenile skipjack (20-35 cm) were found in parts of the Western Pacific (Lehodey *et al.*, 2003). This phenomenon can be explained by the high primary productivity. It was reported that there was a huge phytoplankton bloom about four to eight months earlier in the equator at 165°E (Murtuggude *et al.*, 1999). Lehodey *et al.* emphasized that this timing matched with the rapid growing season of young juvenile skipjack (Lehodey *et al.*, 2003). However the mechanism linking primary production to skipjack production cannot be examined at this moment because intensive zooplankton data are not available in tropical areas. Moreover, high recruitment is not always linked to a high catch. For instance, the total catch was not increased in 1991/92 El Niño event.

Results from previous studies indicated a positive effect of El Niño event and skipjack catches. In this study, however, the statistical cross-correlation between SOI and catch was not significant. Although the fishery is influenced by environmental factors, it also might be affected by other factors (i.e., economic and political relationship). Therefore the statistical relationship between El Niño events and the skipjack catch was lower than originally anticipated. However, the relationship between the SOI and SST were examined only two areas and analyses of broader geographical areas might produce different results.

3. Effects of ENSO on captured skipjack GSI & mean length

Seasonal change did not cause any detectable effects on length and GSI. Like many species of tropical fishes, skipjack tuna spawn continuously through a year, and larger fish (> 40 cm) have matured gonads throughout the year.

Matsumoto *et al.* (1984) confirmed this by showing the polymodal distribution of ova diameter and showing absent of spawned-out fish. These observations confirmed that skipjack are multiple spawners. The GSI of skipjack and SOI had a negative correlation with no time lag. However, when a time lag between two factors was considered, the correlation was positive and the highest correlation was greatest with a time-lag of 8-9 months. This phenomenon inferred that the biological responses to environmental change take time. Therefore, when the biological lag is considered, the GSI has a negative response to El Niño events.

Because skipjack is a high-fecundity pelagic spawner with pelagic eggs, the loss of eggs by predation and transport must be very high, although this cannot be measured at the present study. Although the GSI may reflect the condition of maturation of skipjack, Schaefer, (2003) questions the validity of using the gonosomatic index for classification of maturity activity without carrying out other methodologies, like test for oocytes. However, the GSI responds to the SOI signal in my study, though I cannot explain the process how El Niño affects on GSI. To delineate this process clearly, the spatial fishing data should be considered and histological examination should be accompanied with GSI, in future study.

From analysis of the length variation, all of three environmental factors affect on growth. As I pointed-out earlier, because the biological responds from the environmental change take time, time-lag should be considered. Cross-correlation of mean length and SOI showed a positive relationship after a 5 month time lag. El Niño had a negative influence on mean length. I cannot determine what processes during ENSO caused a negative effect on growth. There are two hypotheses to explain why mean length decreased after El Niño events: one is that skipjack size decreased during El Niño and the other is small skipjack recruited to the fisheries. As I suggested previously based on Lehodey *et al.*(2003), there were large numbers of juvenile skipjack (20-35 cm) found in parts of the Western Pacific at the end of 1998, after 1997/98 El Niño event. Therefore, the second hypothesis appears to be the most probable explanation. However, it cannot be tested without age data from catches. Similar phenomenon may be detected from SCTB length frequency data. The graphical illustration (Fig. 10) showed the regime-specific growth pattern at each discrete period, and it seemed to be related with ENSO. Several remarkable ENSO events occurred since late 1980s. Three of El Niño events and one of La Niña are distinguished: the 91/92 Niño, 97/98 Niño, 2002 Niño, and the 98/99 Niña. Positive modes of length anomalies changed to negative mode after several month of an El Niño event. On the other hand, negative modes from 1993-1998, to positive after the La Niña event in late 1998.

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