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Distributional Ecology of the Bigeye Tuna (*Thunnus obesus*) and
Yellowfin Tuna (*Thunnus albacares*) in the Pacific Ocean
太平洋におけるメバチ・キハダの分布生態に関する研究

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Chapter 1. Introduction

1.1 Ecology of tuna species

Tuna is an economically important fish that belongs to the genus *Thunnus*, tribe *Thunnini*, and family Scombridae. There are a total of eight species in genus *Thunnus*, including yellowfin tuna (*T.albacares*), bigeye tuna (*T.obesus*), longtail tuna (*T.tonggol*), southern bluefin tuna (*T.maccoyii*), Atlantic bluefin tuna (*T.thynnus*), Pacific bluefin tuna (*T.orientalis*), blackfin tuna (*T.atlanticus*), and albacore tuna (*T.alalunga*). They are essentially distributed between 45°S and 45°N in oceans all over the world (Sund et al., 1981), and a large percentage of their body is composed of fat, which makes them popular at the dining table. In order to keep up with the worldwide demand for seafoods such as sushi and sashimi, many tuna populations are being significantly overfished. The bigeye tuna and yellowfin tuna play a crucial role in the fisheries economy (Lu et al., 2001). According to the statistical data of FAO, the bigeye tuna and yellowfin tuna account for almost 85% of the world's total catch for main tuna species in 2010 (Fig. 1). Similar to other tuna species, these two species are highly migratory fish with extremely excellent swimming ability and a penchant for finding suitable habitats with optimum water temperature and high prey abundance (Bardach & Matsuda, 1980).

The bigeye tuna inhabits tropical and subtropical waters ranging from 13–29°C in the Pacific, Atlantic, and Indian Oceans. In daytime, it moves to relatively deep waters at around 400–500 meters below the sea surface while it returns to warm shallow waters at night (Fuller et al., 2015; Howell et al., 2010; Matsumoto, 2013; Schaefer & Fuller, 2002, 2010; Schaefer et al., 2007). Its diet covers a variety of fish species, cephalopods and crustaceans (Jong-Bin et al., 1997; Li et al., 2019; Sigeyuki, 1959, 1960; Tsuchiya et al., 1998; Zhen, 2014). It can grow to over 250 cm in length and up to 210 kg, with a longevity of around 15 years (Farley et al., 2004; Zhen, 2014). Spawning events take place where water temperatures reach at least 24°C throughout the year and migration occurs annually between tropical reproduction areas and subtropical feeding grounds (P. Lehodey et al., 2010).

The yellowfin tuna occupies many of the same areas as the bigeye tuna. It is considered one of the most tropical species of tuna, as its population density is highest between 30° S and 30° N (SUND et al., 1981). It often dwells at depths of around 100 m (Dagorn et al., 2006; Schaefer et al., 2007), mainly occurring in sea areas where water temperature is between 18 to 31°C (Suzuki, 1994). The yellowfin tuna is slightly smaller than the bigeye tuna. It can grow to over 200 cm and up to 200 kg, with a longevity of about 9 years. Similar to the bigeye tuna, the yellowfin tuna is also highly fecund and maintains similar spawning environment preferences. Yellowfin juveniles eat small zooplankton and adults eat large bony fish and squid (Watanabe, 1958). Both the bigeye tuna and the yellowfin tuna tend to school with other tuna species, porpoises and even floating subjects, but this behavior diminishes as they grow up.

The main methods for fishing these tuna species are longlines and purse-seine nets (Evans et al., 2008). For tens of hundreds of years, the bigeye tuna and yellowfin tuna have been caught and transported worldwide, functioning as an important food resource (Hanamoto, 1987). Therefore, it is

crucial to implement proper resource management with a clear understanding of the impacts of both fishing activities and environmental changes on tuna populations. However, with having focused on excessive fishing ever since MSY (maximum sustainable yield) theory was proposed, information of the effects of environmental changes on tuna's resource changes remains being paid little attention (Kawasaki, 2005). Therefore, the resource management decisions are rather defective.

1.2 The relationships between tuna resource management and environmental changes

There are five regional fisheries management organizations (RFMOs) that assess the tuna resources: the Inter-American Tropical Tuna Commission (IATTC), the Western & Central Pacific Fisheries Commission (WCPFC), the International Commission for the Conservation of Atlantic Tunas (ICCAT), the Indian Ocean Tuna Commission (IOTC), and the Commission for the Conservation of Southern Bluefin Tuna (CCSBT). According to the 2018 report by IATTC, the bigeye tuna in the eastern Pacific Ocean (EPO) are continuing to decline (IATTC, 2019). Moreover, the average weight of bigeye caught by fishers has been dramatically decreasing and remained at less than 7 kg ever since 2005 (Xu et al., 2019). This indicates that bigeye stocks are under increased fishing pressure. In the western and central Pacific Ocean (WCPO), the stock and spawning biomass has also been decreasing since the 1950s (SC14, 2018). Indicators of relative abundance for the yellowfin tuna in EPO is low, implying a low population size (IATTC, 2019). In WCPO, biomass of the yellowfin tuna is declining in most tropical and temperate areas. From a long-term perspective, the total global nominal catch for the bigeye tuna and yellowfin tuna has increased approximately tenfold from 1950 to 2010 according to statistical data from the FAO. Because of overfishing, the bigeye tuna and yellowfin tuna have been put on the IUCN red list, ranked as vulnerable and near threatened species, respectively. This indicates an urgent need to implement appropriate resource management for further sustainable utilization.

Previous studies have shown that many environmental factors can impact the distribution of the bigeye tuna and yellowfin tuna. For example, water temperature (Block et al., 1997; Fuller et al., 2015; Hyder et al., 2009; K. W. Lan et al., 2013; Rajapaksha et al., 2013; Song et al., 2008), salinity (Yen et al., 2012; Zhen, 2014), chlorophyll (K.-W. Lan et al., 2017; Setiawati et al., 2015; Yen et al., 2012; Zagaglia et al., 2004), and dissolved oxygen (John Hampton et al., 1998; Song et al., 2008) could influence the distribution patterns of these tuna species. Increased knowledge of how environmental changes affect distribution changes could play a vital part in tuna resource management. However, the work of all these RFMOs are still based on stock management by using population dynamical models and lacking of an integration of environmental changes (Lehodey et al., 2008). In addition, most of the previous studies focused on a small spatiotemporal scale. Therefore, the relationships between the distribution of these tuna species and long-term environment changes remain unexplored, and the method of resource management needs to be improved.

1.3 Objective

As stated above, it is of great importance to conduct appropriate management for the bigeye tuna and yellowfin tuna in order to stabilize stocks. Currently, long-term environmental changes that affect the distribution of these tuna species are rarely the focus of resource management plans, resulting in imperfect conservation for these tuna species. Using long-term and wide-range fishery data sets, distribution changes of the bigeye and yellowfin tunas are investigated by principal component analysis and their relationships with different environmental changes are clarified by correlation analysis in order to improve future resource management.

Chapter 2. Materials and methods

2.1 Catch data

2.1.1 Catch data of tuna species

Catch data of the bigeye tuna and yellowfin tuna from 1971 to 2013, covering the whole Pacific Ocean, was obtained from the National Research and Development Agency Japan Fisheries Research and Education Agency (NRIFS FRA). The spatial range of the catch data was shown in Fig. 2. The data were georeferenced in 5° grid longitude and latitude, keeping a record of monthly catch in number and weight for the bigeye tuna, yellowfin tuna, and albacore tuna as well as the number of hooks used in each grid. The data set was used to analyze the distribution of the bigeye tuna and yellowfin tuna in the Pacific Ocean from 1971 to 2013.

2.1.2 Catch data of other fish species

Catch data of other fishes such as Japanese sardine (*Sardinops melanostictus*) and Japanese anchovy (*Engraulis japonicus*) were collected from the Statistics Bureau of Japan (<https://www.e-stat.go.jp/dbview?sid=0003238631>). These data were used to estimate the resource changes of prey species of these tuna species.

2.2 Environmental data

2.2.1 Sea surface temperature data

The global sea surface temperature (SST) data sets were downloaded from the Tokyo Climate Center website, the Japan Meteorological Agency (https://ds.data.jma.go.jp/tcc/tcc/products/el_nino/cobesst/cobe-sst.html). The data sets are provided with a resolution of 1° longitude and 1° latitude from 1971 to 2013 and a monthly temporal resolution. SST data were averaged to 5° in both latitude and longitude.

2.2.2 Other meteorology indices

Meteorological indices, such as Nino 3.4 index, were obtained from the National Oceanic and Atmospheric Administration (NOAA) website (https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/) in order to evaluate long-term meteorological changes.

2.3 Data analyses

2.3.1 Principal Component Analysis

The Principal Component Analysis (PCA) was used to reduce the dimensionality of a data set and to extract the dominant patterns or principal components (Abdi & Williams, 2010; Wold et al., 1987). It is a multivariate method that has applications in many fields, such as environmental science,

biology and medical science. Generally, data pre-treatment is needed in order to effectively conduct PCA. If missing data is included in a data set, PCA will not be conducted successfully.

Catch per unit effort (CPUE), which can be used to represent fish abundance (Bertrand et al., 2002), is usually calculated by dividing catch in number by the number of hooks. In this study, catch number per 1,000 hooks was initially calculated using equation (1) and was used as CPUE.

$$CPUE = \frac{N_{catch}}{N_{hooks}} \times 1000 \quad (1)$$

N_{catch} : catch in number of individuals.

N_{hooks} : number of hooks.

Since CPUEs may be outside of the acceptable margin of error if data within a grid cell is missing for many years, some areas were removed in consideration of accuracy. Outliers were considered areas with consistently zero CPUE or lack more than half of its data during the years of analysis. The rest of the data were filled through linear imputation both spatially and temporally with the latter ultimately selected because of a smaller dispersion of CPUE.

The most important principal component is called PC1, and the second important principal component is called PC2. The principal component score of a specific year is the standardized value of the sum of product of eigenvectors times CPUEs in each grid cell, which is expressed by equation (2).

$$S_i = \sum_{j=1}^n CPUE_{ij} \times Eigenvector_{ij} \quad (2)$$

S_i : principal component score of year i

$CPUE_{ij}$: CPUE of year i, grid cell j

$Eigenvector_{ij}$: Eigenvector of year i, grid j

n : the number of grid cells

Principal component scores were calculated by using package “prcomp” of R (Package stats version 3.6.1). Score and contribution of each principal component were outputted by the package simultaneously.

2.3.2 Correlation Analysis

In order to investigate the relationships between the distributions of tuna species and environmental factors, such as changes of SST and catch of dominant prey species, the Spearman rank correlation coefficient was used for the data were not normally distributed (McCrum-Gardner, 2008). This coefficient can be used to measure the correlation of two variables, and correlation coefficients can be calculated by equation (3).

$$r_s = \frac{1-6 \sum_{i=1}^n d_i^2}{n(n^2-1)} \quad (3)$$

r_s : correlation coefficient

d_i : the difference between ranks for each x_i, y_i data pair

n : the number of data pairs

r_s is used to evaluate the relevance, ranging between -1 and 1. The higher the correlation coefficient is, the higher correlation the two variables have. There is a significant difference when the p value is less than 5% (McCrum-Gardner, 2008).

2.3.3 Mann-Whitney U Test

Mann-Whitney U Test is a method that can investigate whether there is a significant difference between two sample groups which can be considered as come from the same population. There is a significant difference when the p value is less than 5%.

2.3.4 Analysis Tools

All statistical analyses were conducted using statistical software R (Version 3.6.1). All color maps of eigenvectors and CPUEs were plotted using Generic Mapping Tools (GMT, Version 5.4.4).

Chapter 3. Distribution changes of hooks, tuna species and SST

3.1 Annual changes of hooks

The total number of hooks used in Japanese longline fishery in 1971-2013 were plotted in Fig. 3 and it generally shows a decreasing trend. This result may have been the result of the recession of Japanese pelagic fisheries. One of the reasons for the decline of the Japanese longline fishery is the removal of the ban on imported beef in 1991. There is a strong negative correlation between the total weight of imported beef and the number of hooks ($r_s = -0.55$, $p < 0.001$). In addition, grid cell uncovered by the Japanese longline fishery from 1971 to 2013 was shown in Fig. 4. The number of grids has been increasing year by year, nearing 300 in 2013.

PC1 score for the number of hooks used in fishery activities declined slightly from 1971 to 1981 and then increased markedly from 1982 to 2013, with a contribution of 23.1% (Fig. 5-a). A colored map of eigenvectors indicating increases and decreases in CPUE for each grid cell across 1971-2013 showed a concentration of positive values in the northern areas of the North Pacific Ocean (NPO), the coastal areas near Solomon Islands, Australia, and South America (Fig. 5-b). This indicates that the number of hooks used in these areas increased during 1981-2013.

PC2 score (13.1%) decreased dramatically from 1971 to 1988, but has notably improved toward 2013 (Fig. 6-a). A colored eigenvector map similar to the one created for PC1 was also created for PC2 to demonstrate changes in the number of hooks. Negative eigenvector values were concentrated in the eastern equatorial areas (Fig. 6-b). This indicates that more hooks were used in the eastern equatorial areas from 1971 to 1988, but there was a reduction in hooks in the same area from 1989-2013.

3.2 Annual and monthly distribution changes of bigeye tuna

The PC1 score (23.3%) of the bigeye tuna has been on the rise despite annual fluctuations, with a change from negative to positive values in 1993 (Fig. 7-a). Positive eigenvectors were concentrated in the West Pacific Ocean (WPO) with negative values in the East Pacific Ocean (EPO) (Fig. 7-b). This indicates that the distribution of the bigeye tuna has shifted from the EPO to the WPO in the 1990s. This was further confirmed in 1986, 2002 and 2013, when the areas of high CPUE moved westwards (Fig. 8).

The PC2 score (7.9%) decreased into the negatives from 1971 to 1985 and then started to shift back to positive values in 2002 (Fig. 9-a). Positive eigenvectors values were found in the central North Pacific Ocean (NPO), and negative values were relatively concentrated in the eastern equatorial areas and coastal areas of the WPO (Fig. 9-b). This shows that the bigeye tuna gradually gathered in the eastern equatorial areas and coastal areas of the WPO until the mid-1980s and then slightly went back into the central NPO until 2006.

Annually, PC1 score (27.6%) rose from January, peaked in August and September, then fell until December (Fig. 10-a). Positive eigenvector values were recorded in subtropical areas (20-40°N) of the

North Pacific Ocean and throughout the South Pacific, while negative values were found around 0-20°N (Fig. 10-b). This pattern implies that in the North Pacific Ocean, the bigeye tuna in tropical areas move to feed in subtropical waters in summer and return to the tropics to spawn in autumn.

3.3 Annual and monthly distribution changes of yellowfin tuna

The PC1 score of the yellowfin tuna (19.1%) fluctuated in negative values from 1971 to 1995 and then dramatically increased to positive values (Fig. 11-a). Several positive eigenvector values showed up in waters off eastern Australia and southwestern Mexico, and other areas showed negative values (Fig. 11-b). No obvious distributional pattern was observed.

The PC2 score (11.6%) fell from 1971 to 1993 and then increased toward 2013 (Fig. 12-a). The colored map of eigenvectors showed that positive eigenvector values were concentrated in the coastal equatorial areas and the northeast Pacific (Fig. 12-b). This indicates that the distribution of the yellowfin tuna shifted from coastal equatorial areas and the northeast Pacific to the northwest Pacific from 1971 to 1990s. After the 1990s, CPUE of the yellowfin tuna rose again in coastal equatorial areas and the northeast Pacific.

The PC1 score of the yellowfin tuna (25.4%) showed a similar seasonal distribution pattern as that of bigeye tuna, but PC1 score of the yellowfin tuna were highest in June and July (Fig. 13-a). Positive eigenvectors were concentrated around 25°S-20°N (Fig. 13-b). This suggests that the yellowfin tuna migrates to subtropical waters in winter for feeding and then returns to tropical areas in summer for reproduction.

3.4 Annual changes of SST

The PC1 score of SST (25.5%) fluctuated remarkably from 1971 to 2013, peaking in 1972, 1982-1984, 1987, 1992 and 1997 (Fig. 14-a). Positive eigenvectors were concentrated in the area from the meridian to the most eastern equatorial waters off the American continent (Fig. 14-b). This fluctuation showed that water temperature in the eastern equatorial areas increased in the years mentioned above and fell in other areas. These results are typical of El Niño and La Niña events, as verified by the correlation analysis of SST PC1 and Nino 3.4 index in which the correlation coefficient is as high as 0.85 (Spearman rank correlation test, $p < 0.01$) (Fig. 15).

The PC2 score of SST (17.7%) increased throughout 1971-2013 (Fig. 16-a), and almost the entire Pacific Ocean had positive eigenvector values (Fig. 16-b). This increasing pattern indicates that the SST in the Pacific Ocean rose from 1971 to 2013, implying a potential manifestation of global warming.

Chapter 4. Correlations between tuna distribution and environment changes

4.1 Correlations between annual distribution changes of bigeye tuna and dominant prey species

Distribution changes of the bigeye tuna are related to distribution fluctuations of their prey species. The PC1 of the bigeye tuna suggested that its distribution shifted from EPO to WPO in 1990s (Fig. 7). This pattern may be the result of changes in distributions of the dominant prey species for bigeye tuna: Japanese sardine and Japanese anchovy. In the 1980s, the catch of Japanese sardine increased dramatically, reaching more than tenfold catch in the 1970s, and then declined markedly in the 1990s (Fig. 17). Meanwhile, its distribution shrank from EPO to WPO. On the other hand, the catch of Japanese anchovy, whose distribution was essentially confined within 170°E, was relatively low in 1980s and started to increase prominently in 1990s (Fig. 17). The PC1 score of bigeye tuna had a strong negative correlation with the Japanese sardine landings ($r_s = -0.70$, $p < 0.01$) and a positive correlation with the Japanese anchovy landings ($r_s = 0.51$, $p < 0.01$).

4.2 Correlations between annual distribution changes of bigeye tuna and SST

SST is one of the most important environment factors that affect the distribution of bigeye tuna. The westward distribution shift mentioned above is also connected with water temperature changes. Areas with high CPUE (grid cells in which CPUE is higher than 60% of the maximum CPUE) were selected in both 1971-1993 (when PC1 scores of bigeye tuna remained in the negatives) and 1994-2013 (when PC1 scores were positive). There is a significant difference between the SST values of high catch areas in 1971-1993 (23.1°C) and in 1994-2013 (25.2°C) (Mann-Whitney U test, $p < 0.05$) (Fig. 18). In addition, SST was compared between Area 1 and Area 2 where positive and negative eigenvectors of PC1 were respectively concentrated (Fig. 19-a). It is clear that the SSTs of most grid cells increased in Area 1 and decreased in Area 2 (Fig. 19-b). The differences between SST values of Area 1 and Area 2 are statistically significant (Mann-Whitney U test, $p < 0.05$) (Fig. 20). Mean SST difference of Area 1 and Area 2 are 0.25°C and -0.05°C, respectively, indicating that the bigeye tuna tends to move to warmer waters.

4.3 Correlations between annual distribution changes of bigeye tuna and hooks

The PC2 of the bigeye tuna suggests that the bigeye tuna gradually gathered in the eastern equatorial areas and coastal areas of the WPO until the 1980s and then some of the tuna returned to the central NPO. This distribution shift could have been due to the development of tuna fishery methods and the change in target species for Japanese longline tuna fishery. There were negative eigenvectors of PC2 in both bigeye tuna CPUE and hook numbers in eastern equatorial areas, and a strong positive correlation between the PC2 of bigeye tuna CPUE and hooks ($r_s = 0.76$, $p < 0.01$). At the same time, analysis of the longline catch data revealed that the percentage of catch number of the bigeye tuna started to decrease in the early 1990s, while albacore tuna landings kept increasing (Fig.

21). This indicates a shift of target species for Japanese longline fisheries which are from bigeye tuna to albacore tuna.

4.4 Correlations between annual distribution changes of yellowfin tuna and hooks

PC2 indicated that the distribution of yellowfin tuna in the coastal equatorial areas and the eastern areas of the NPO moved to the western areas of the NPO from 1971 to the 1990s, and then shifted back to these areas after 1990s. Like the bigeye tuna, the PC2 of the yellowfin tuna could have been impacted by changes in the Japanese longline fishery. Both the PC2 of the yellowfin tuna CPUE and the number of hooks had positive eigenvectors in coastal equatorial areas in the WPO and the eastern areas of the NPO. In addition, there is a significant correlation between PC2 of hooks and PC2 of the yellowfin tuna ($r_s = 0.87, p < 0.05$). Moreover, the percentage of catch number of the yellowfin tuna decreased ever since the end of 1970s (Fig. 21), indicating that the target species for Japanese longline fisheries shifted from yellowfin to other tuna species since the second half of the 1970s.

Chapter 5. Discussion

5.1 Annual changes in the number of hooks

The decline of fishing efforts is likely due to the recession of Japanese longline fishery. In 1973, the oil shock occurred and oil price increased remarkably, causing increase in oil expenses and fishery activity costs. In 1977, the Act on Territorial Waters and Contiguous Water Area was revised and pelagic fishing activities were more heavily restricted. This amendment in law has tremendously affected the Japanese pelagic fishery. In 1978, the second oil shock happened. In 1981, pelagic longline fishing fleets for tunas plummeted in number. In 1985, imports of tuna from Taiwan (China) spiked. In 1991, the ban of beef import was lifted. The total weight of imported beef is negatively correlated with the total number of hooks, which decreased demand of fish to some extent. In 1999, pelagic longline fishing fleets for tuna were reduced again. These incidents may have accelerated the depression of Japanese longline fisheries (Miura, 1990). As a consequence, the number of hooks used in fishery activities and grid cells covered by Japanese longline fishery has been decreasing year by year and the accuracy of catch data might be negatively affected.

5.2 Relationships between distribution changes of bigeye tuna and regime shift

The PC1 of the bigeye tuna indicated a distribution shifted from the EPO to the WPO. This pattern can be explained by regime shift (Kawasaki, 2010; Noguchi-Aita et al., 2018; Yatsu & Takahashi, 2013), a phenomenon when certain kinds of fish dominated in different time periods within an interdecadal interval (Kawasaki, 2002; Sugimoto, Kimura, & Tadokoro, 2001; Yatsu & Takahashi, 2013). Regime shift can be seen in many different environments, including atmospheric, oceanic, as well as the interface between the two environments (Kawasaki, 2010; Yatsu, 2009). It has been widely accepted that a great regime shift occurred in the 1990s, with a dramatical decline of the resource of Japanese sardine and remarkable increase of Japanese anchovy (Chavez et al., 2003; DeYoung et al., 2004; Tian et al., 2006). Japanese sardine is a common prey for numerous large fishes inhabits in waters around Japan. Its distribution areas increase as their resources. In 1980s, when the Japanese sardine landings were sky-high (Tian et al., 2006), the distribution crossed the date line and reached 165°W. In the 1990s, when the resource declined, the distribution retreated to around 155°E (Kazunori, 1991). On the other hand, Japanese anchovy, another important prey species found in the coastal waters of Japan, similarly demonstrated changes in distribution in the 1990s (Takahashi et al., 2001). In 1980s, the total catch of Japanese anchovies (50000-100000 t) was just half of that of the mid 1970s (100000-250000 t) (Takahashi et al., 2001). In 1990s, when total catch increased sharply to over 200,000t (Takahashi et al., 2001), anchovy distribution was still confined within the 170°E (Nakahara, T. and Ogawa, Y, 1979; Nagasawa, K. and Azuma, T, 1992; Takahashi et al., 2001). That is, in early 1990s, when regime shift occurred, Japanese sardine decreased sharply and distribution shrank from the EPO to the WPO. Therefore, the distribution of the bigeye tuna also moved westwards along with this prime prey. Simultaneously, Japanese anchovy resource boomed in WPO, and this might also

accelerate the westwards distribution shift of the bigeye tuna. The work of Ohshimo et al., (2018), came to a similar conclusion when they examined the stomach contents of 585 bigeye tunas. They found that the percentage of occurrence, mean percentage of abundance and mean percentage weight of Japanese anchovies were 27 times, 118 times, 47 times larger than that of Japanese sardines respectively.

5.3 Relationships between distribution changes of bigeye tuna and SST

The westwards distribution changes also showed a strong correlation with SST. According to previous studies, SST is a vital factor for bigeye tuna habitat selection. From 1971-1993, the average SST of high catch areas was 23.1°C while from 1994-2013, the average SST of high catch areas increased to 25.2°C. This result suggests that the bigeye tuna moved to warmer waters in 1994-2013. In addition, SST differences in Area 1 and Area 2 were also compared. Obviously, SST differences of most grid cells of Area 1, where the bigeye tuna increased, showed positive values. Whereas, SST differences of most grid cells of Area 2, where the bigeye tuna declined, are negative. This result indicates that the bigeye tuna tends to move to warmer habitats.

Lu et al (2001) found increased hook rates in areas where SST increased during the El Niño period and lower hook rates associated with areas where SST declined during the La Niña period. The preference for warmer waters could also explain their findings.

5.4 Relationships between distribution changes of bigeye tuna and hooks

The PC2 of the bigeye tuna showed that its distribution in eastern equatorial areas increased from 1971 to the 1980s and then decreased toward 2006. The PC2 of hooks indicated that the number of hooks used in eastern equatorial areas also increased in 1971-1988, and then decreased towards 2013. Distributional changes of bigeye tuna appear to be related to the number of hooks. The increase of hooks in 1971-1988 is likely due to increased exploitation of bigeye tuna in eastern equatorial areas of the Pacific Ocean. Since the Second World War, Japanese longline fisheries have expanded dramatically (Satoh, 2019a), and a good fishing ground for the bigeye tuna in the eastern equatorial region was developed on the condition of a larger demand of sashimi (NRIFSF, 1986). In addition, according to analysis of the catch data, the percentage of catch in number of the bigeye tuna once surpassed 50% and remained larger than that of the yellowfin tuna and albacore tuna until 1995. In other words, Japanese longline fishery was focusing on the bigeye tuna in the eastern equatorial areas in 1971-1988. It has been stated that the increase in bigeye tuna catch is due to expanding demand for sashimi and the improvement of refrigeration equipment (Satoh, 2019a, 2019b, 2019c). This conclusion was also verified by a habitat-based model that estimated fishing efforts for bigeye tuna in the Pacific Ocean. It was evident from this study that effort increased 250% from the late 1960s to the 1980s (Bigelow et al., 2002).

There are two possible reasons for the decrease in hooks: the immense success of purse seine fishing and the changes in target species for Japanese longline tuna fishery. Purse seine fishing started in the mid-1970s and it was further developed in the 1990s by using fish aggregating devices (FADs) (Satoh, 2019a). Fishermen later discovered that bigeye tuna could be caught efficiently using a purse seine net. Since bigeye tuna has a higher economic value than yellowfin tuna and albacore, it was given priority over the other two species. Therefore, the catch of bigeye tuna through longline fishing declined significantly (Schaefer & Fuller, 2010), while the catch by purse seine increased dramatically in the 1990s (Satoh, 2019a). From 1975-1993, 88% of the total catch for the bigeye tuna in the eastern Pacific Ocean was derived through longline fishery (Satoh, 2019a). In 2018, only 34.8% of the total catch for the bigeye tuna in the eastern Pacific Ocean was derived through longline fishery (Satoh, 2019a). In addition, the percentage of catch in number of the albacore tuna surpassed 30% in 1993 and kept increased towards 2013. It can be considered that the albacore tuna became the main target tuna species for Japanese longline fishery since 1990s. For these two reasons, CPUEs of bigeye tuna in the EPO decreased.

Albacore tuna have two stocks in the Pacific Ocean: the NPO stock and the SPO stock (Ueyanagi, 1969). In the NPO, the longline fishing grounds are between 10-40°N and 120°E-130°W (Kiyofuji, 2019). According to the PC2 of the bigeye tuna, bigeye tuna distribution in the central NPO slightly increased in the 1990s, which may be explained by increased albacore-targeted fishing activities.

5.5 Relationships between distribution changes of yellowfin tuna and hooks

Although eigenvectors of the PC1 of the yellowfin tuna did not show a clear pattern of distributional changes, PC1 score increased dramatically overall from 1995 to 2002. This may be explained by sudden increase of the yellowfin tuna resource. From 1990-1995, dolphin-targeted operations declined due to the dolphin conservation movement. At the same time, the yellowfin tuna catch attached to dolphin-targeted operations also declined, partly causing the catch of the yellowfin tuna decreased, too (Satoh, 2019c). From 1996-2002, the yellowfin tuna population recovered because of elevated recruitment rates (Satoh, 2019c). On the other hand, Japanese longline fishery relatively concentrated in offshore areas near the grid cells that showed positive eigenvector values. Therefore, CPUE in these areas increased dramatically from 1995 to 2002.

The PC2 of the yellowfin tuna indicated that yellowfin distribution shifted from coastal equatorial areas and the eastern NPO to the western NPO from 1971 to the 1990s. After the 1990s, the distribution of the yellowfin tuna slightly expanded in coastal equatorial areas and the eastern areas of the NPO. Longline fishing was mainly conducted in western equatorial areas and the eastern NPO in the first half of the 1970s and from the 1990s to 2013. The distribution changes of yellowfin tuna might also have been reflected by the change of target tuna species for the Japanese longline fishery. The yellowfin tuna was the main target of the Japanese longline fishery from the 1950s to the mid-1970s (Suzuki, 1994). In addition, the yellowfin tuna was heavily fished in coastal areas near the equator (J.

Hampton & Fournier, 2001). This explains that distribution of the yellowfin tuna concentrated in coastal areas near the equator in the first half of 1970s. From the mid-1970s to the 1990s, the target species shifted to bigeye tuna and catch of yellowfin tuna in tropical areas declined. In 1990s, the fishery began to focus more on albacore tuna and hooks used in the WCPO increased. This might have caused high CPUEs of yellowfin tuna concentrated in coastal areas of the WCPO near the equator.

Chapter 6. Conclusions, limitations and future works

This study provided important information on relationships between distribution changes of the bigeye and yellowfin tunas and long-term environmental changes. These findings may play a vital part in the planning of further resource management for sustainable tuna resource utilization. For example, all the RFMOs can take long-term environment changes into consideration to make more precise resource assessment and resource management plans.

Although our dataset covered a wide range of the Pacific Ocean, there were missing values in certain areas. In particular, more than 50% of the data were missing in the central parts of the South Pacific Ocean during the years of analysis. We removed the data points from these areas in order to maintain a certain level of accuracy. Linear imputation was used in this study to interpolate missing values in this data set. Future studies can use data with wider coverage that contain more data in these areas and with less missing data to further increase the data accuracy.

Although the catch data covered almost the entire Pacific Ocean, other countries also started to enter the Pacific Ocean as time goes by. The declined total number of hooks might result from increased fishing competitions with these countries, especially in recent years. Further studies can analyze all landings from major countries who explore the bigeye tuna and yellowfin tuna in the Pacific Ocean and the resulting distribution changes may be slightly different.

In addition, information on the depth of hooks was unfortunately not recorded in this data set. Since the bigeye tuna and yellowfin tuna inhabit in different depths, the depth of fishing gear can influence catch the rate for each tuna species (John Hampton et al., 1998; Hanamoto, 1987b), and therefore specific numbers of hooks used for each tuna species cannot be determined. Consequently, CPUEs were possibly overestimated or underestimated. Future studies can use data that contain the information on hook depths to further increase the assessment of CPUE for two tuna species. However, since there is no big difference between the active depth of the bigeye tuna and yellowfin tuna, the effect of overestimation or underestimation can be assumed as very small.

Although it is considered that there is only one single species for the bigeye tuna and yellowfin tuna in the world, similar studies can be done in the Atlantic and Indian Oceans to examine whether there are different preferences between tunas in different oceans.

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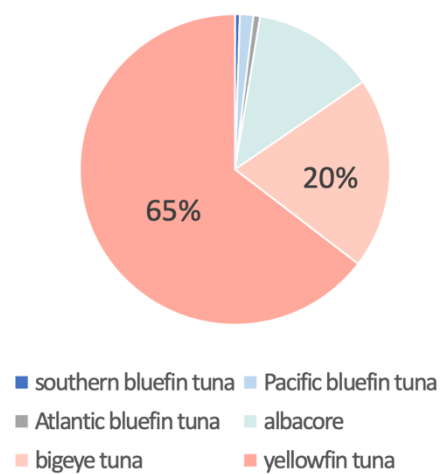


Fig.1 Total tuna catches by species in 2010

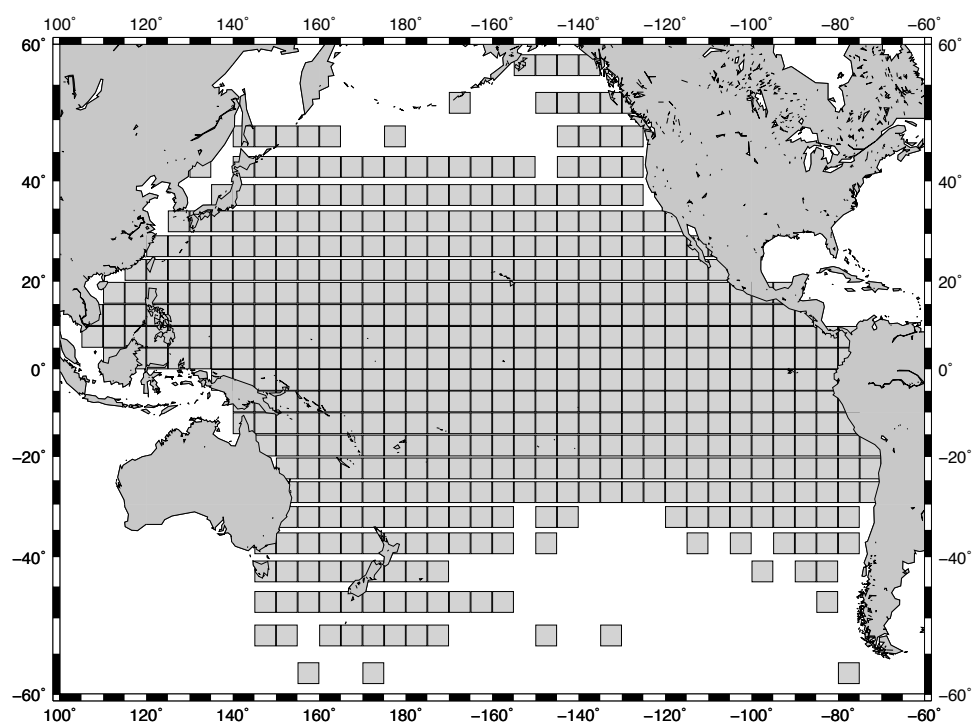


Fig.2 Grid cells covered by Japanese longline fishery

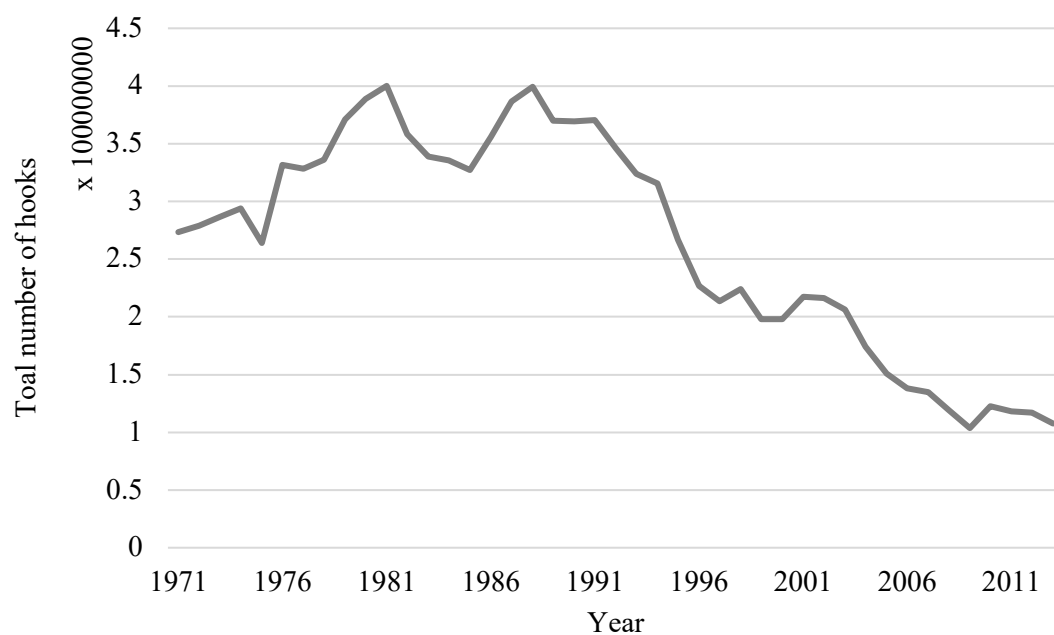


Fig.3 The total number of hooks used in Japanese longline fishery from 1971 to 2013

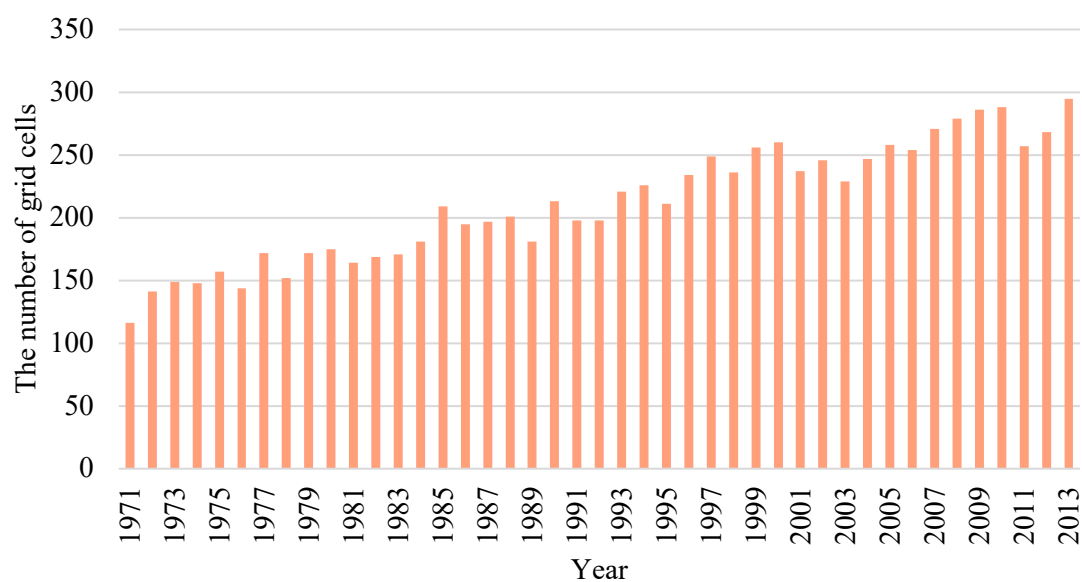
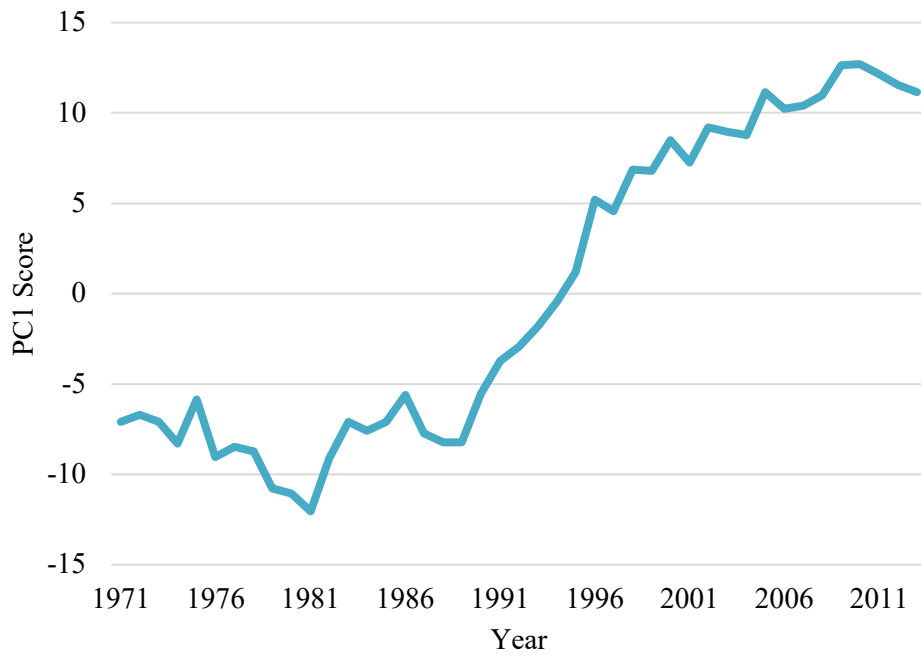


Fig.4 The annual number of grid cells uncovered by Japanese longline fishery in the Pacific Ocean from 1971 to 2013

(a)



(b)

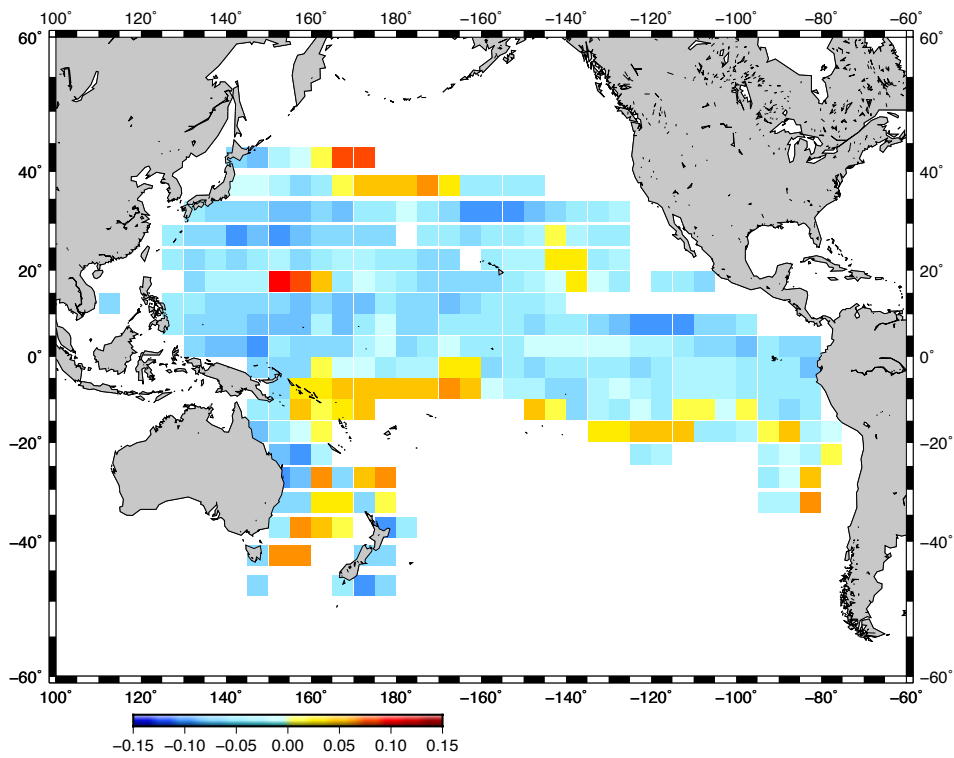
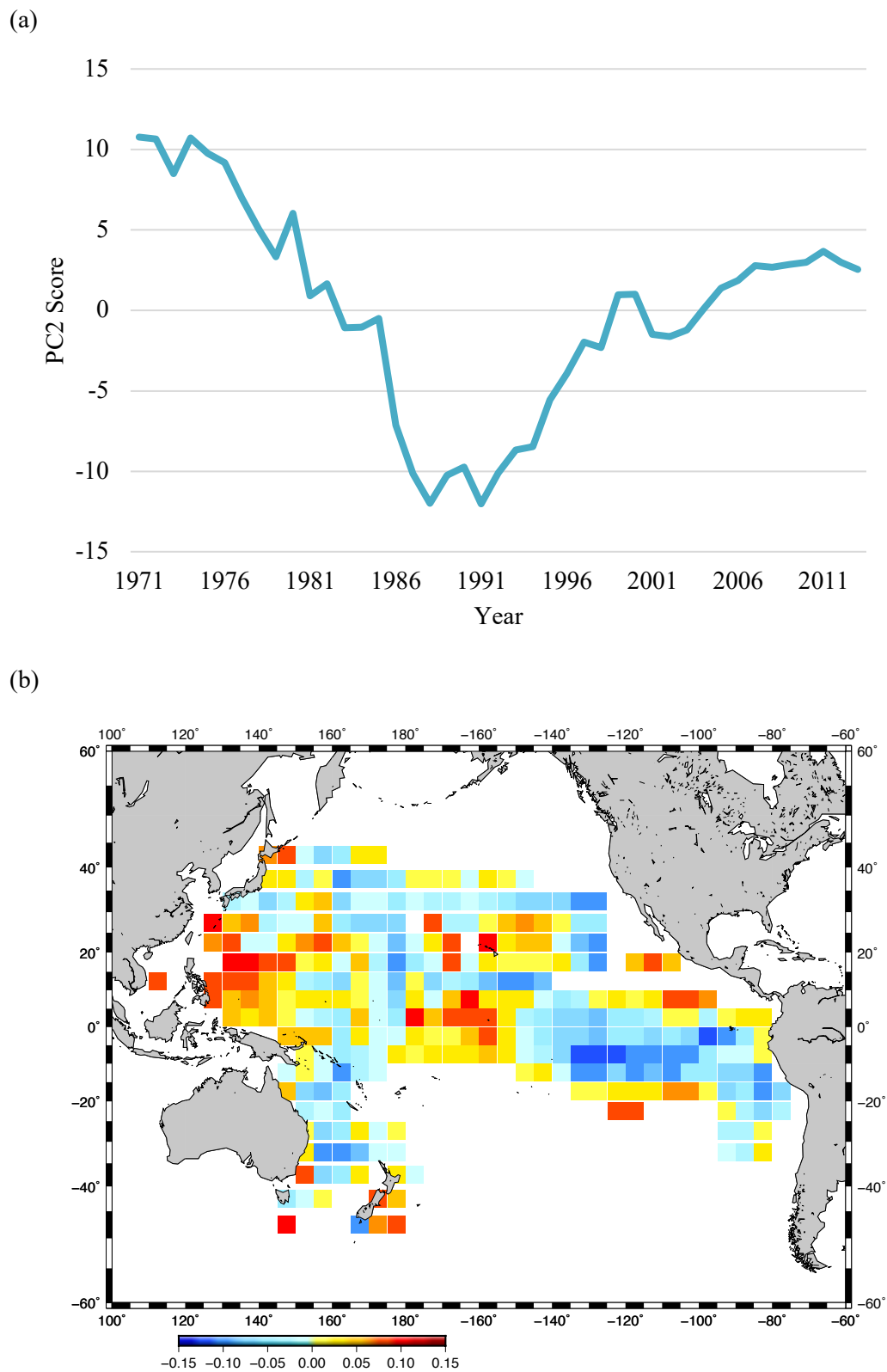
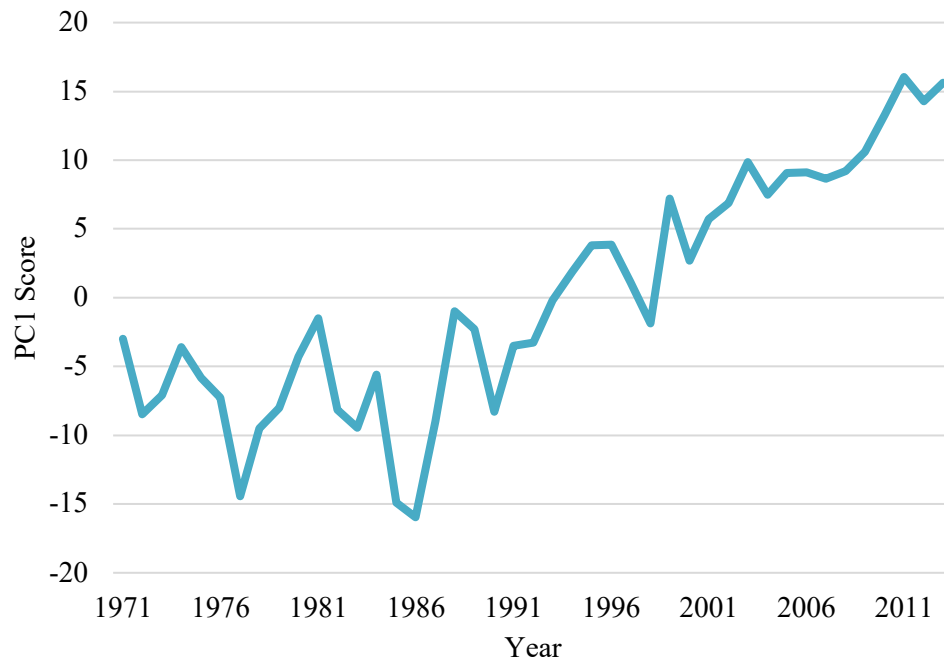


Figure 5. PC1 of annual number of hooks from 1971 to 2013

(a) Annual PC1 score (b) PC1 eigenvector distribution



(a)



(b)

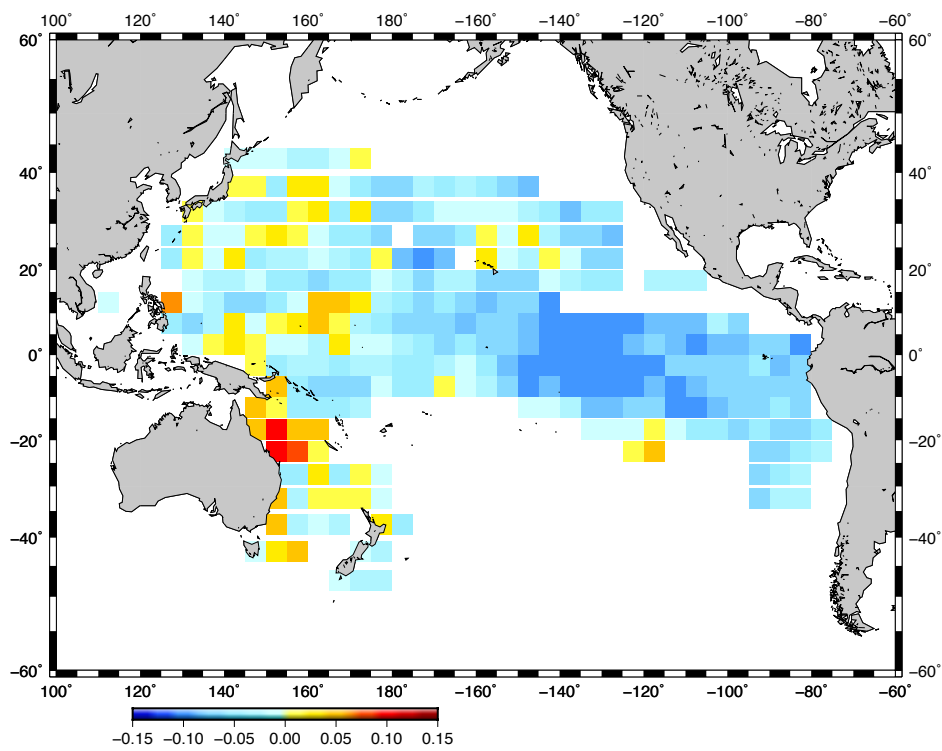
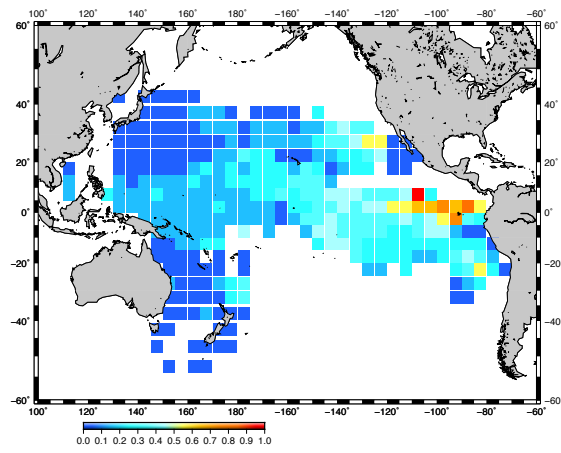


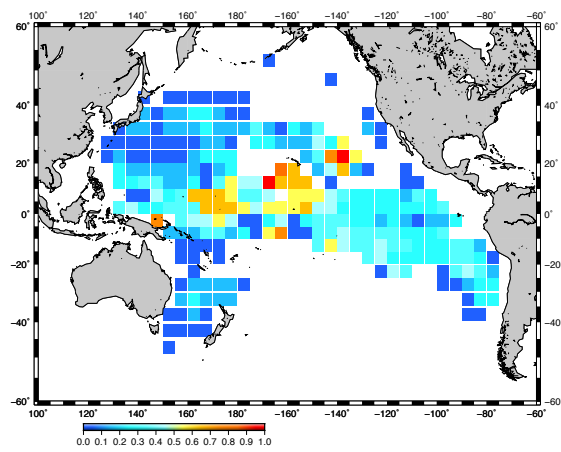
Figure 7. PC1 of CPUE of the bigeye tuna from 1971 to 2013

(a) Annual PC1 score (b) PC1 eigenvector distribution

(a)



(b)



(c)

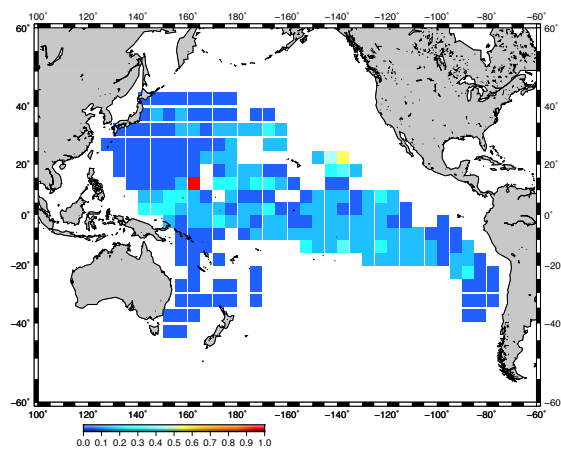
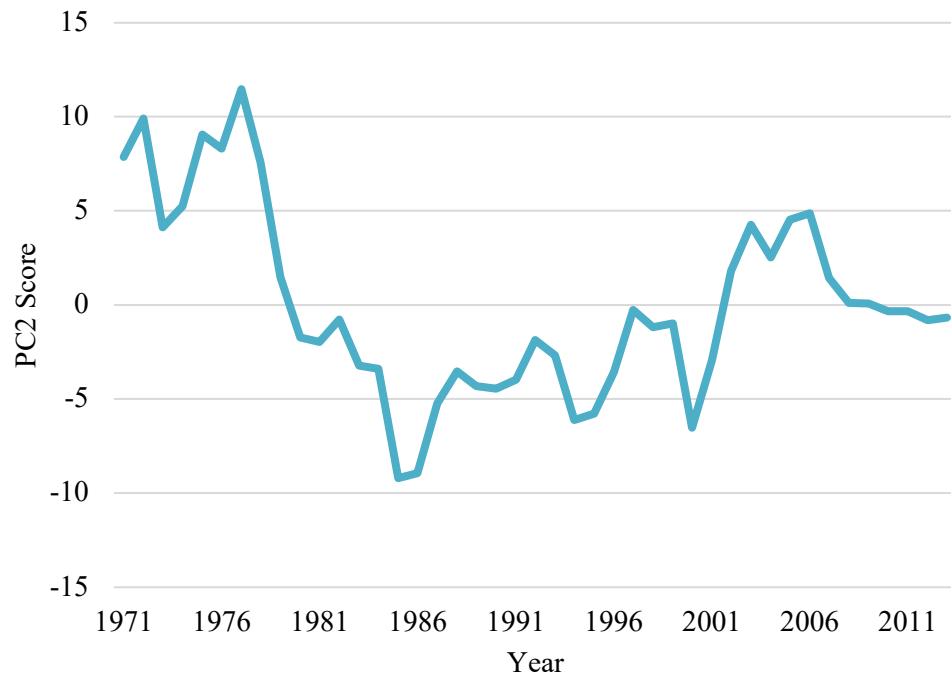


Figure 8. CPUE distribution of the bigeye tuna in (a) 1986, (b) 2002, (c) 2013

(a)



(b)

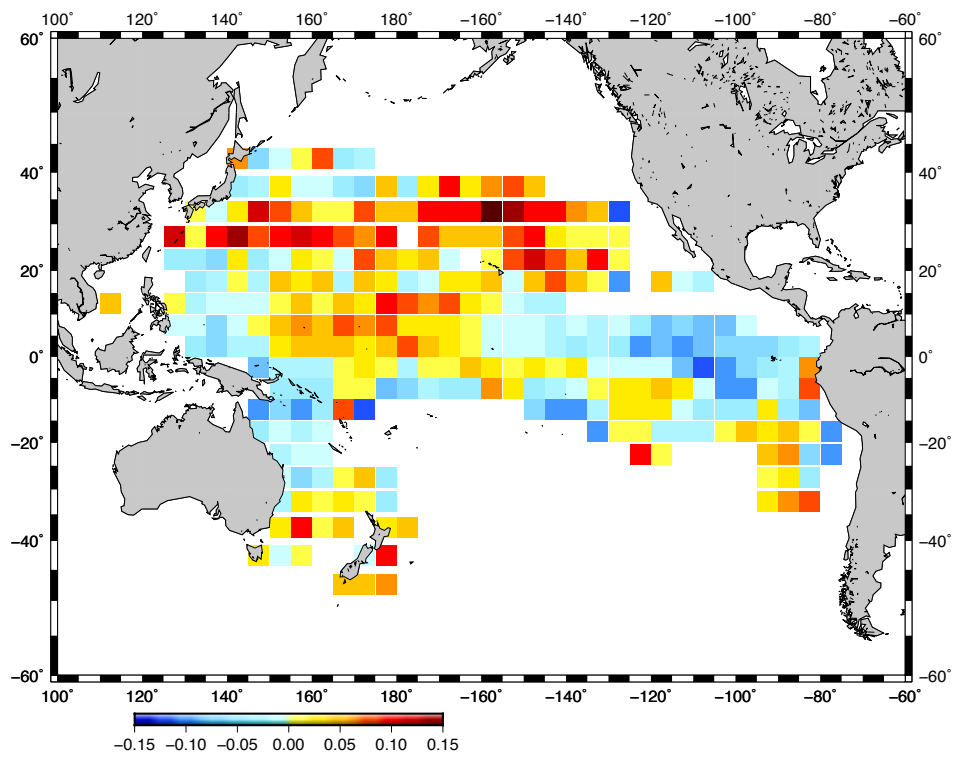
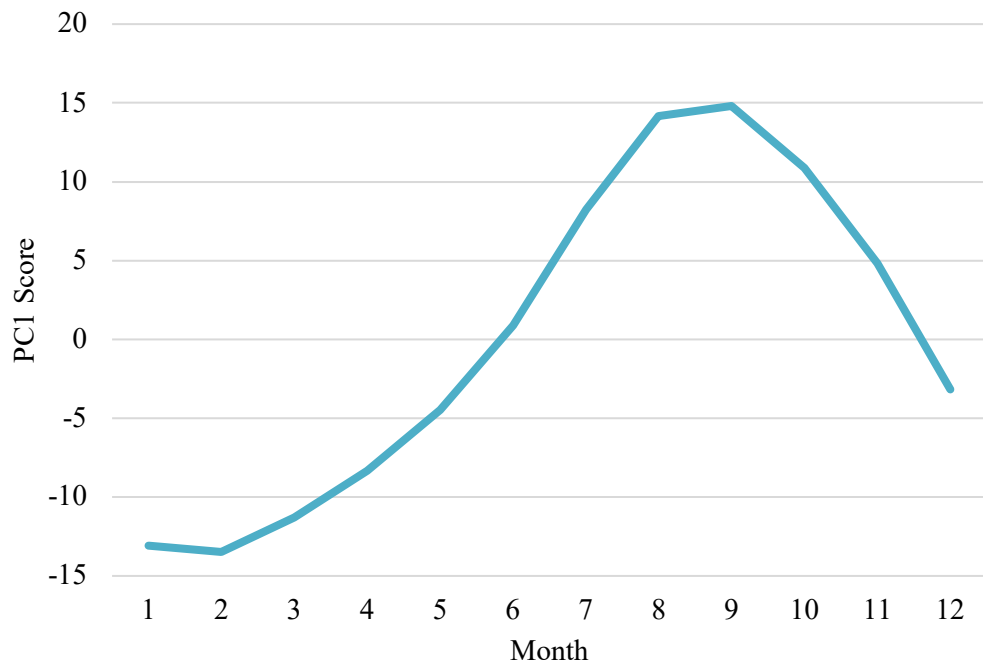


Figure 9. PC2 of CPUE of the bigeye tuna from 1971 to 2013

(a) Annual PC2 score (b) PC2 eigenvector distribution

(a)



(b)

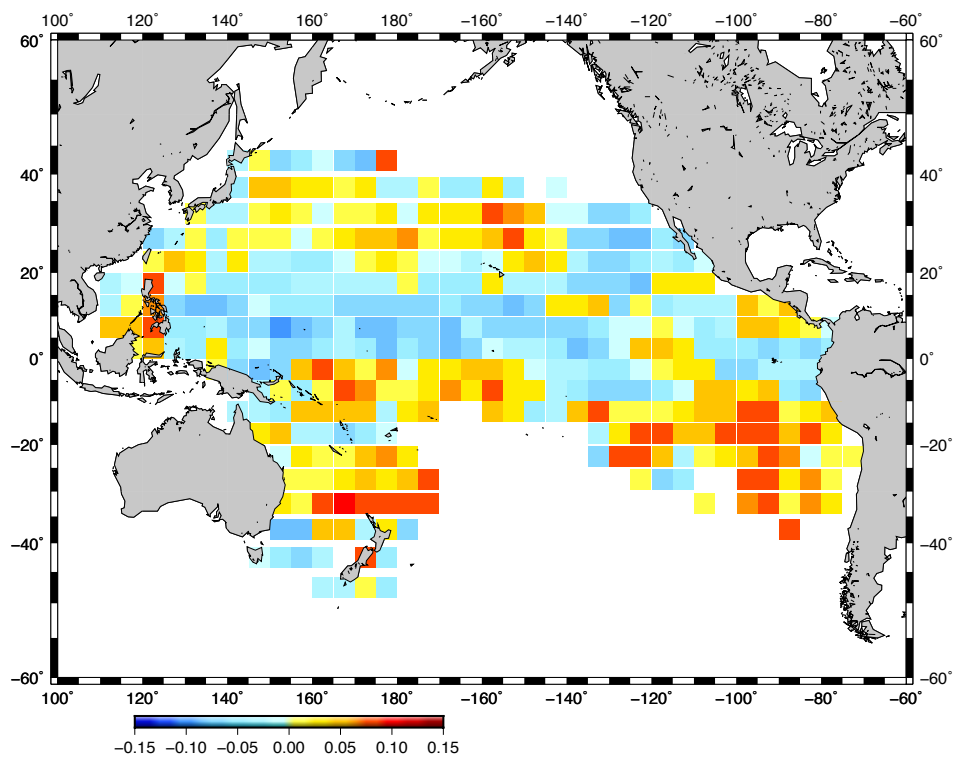
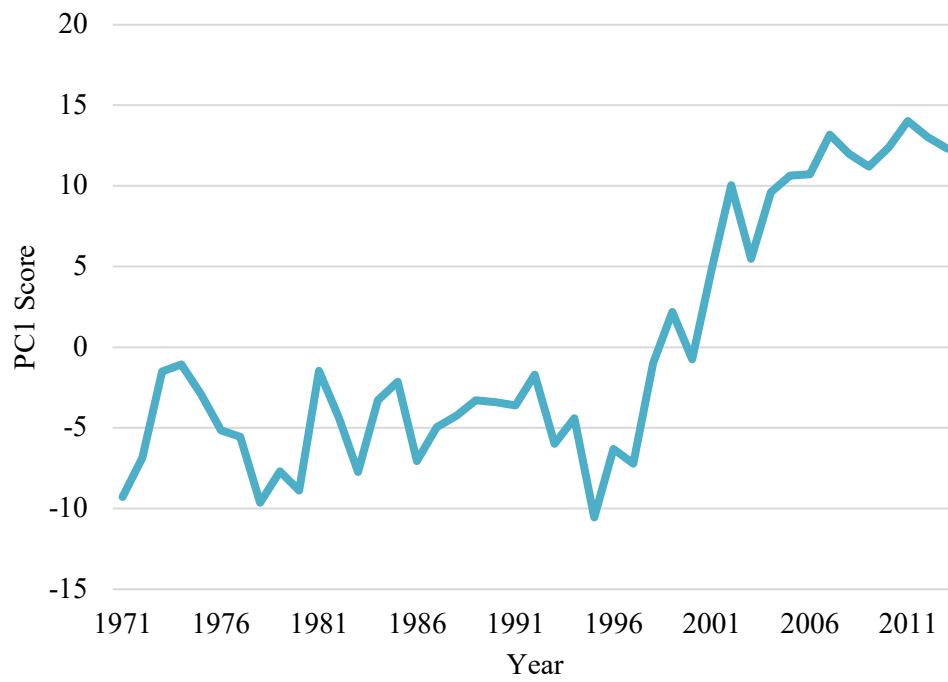


Figure 10. PC1 of monthly bigeye tuna CPUE changes from 1971 to 2013

(a) Monthly PC1 score (b) PC1 eigenvector distribution

(a)



(b)

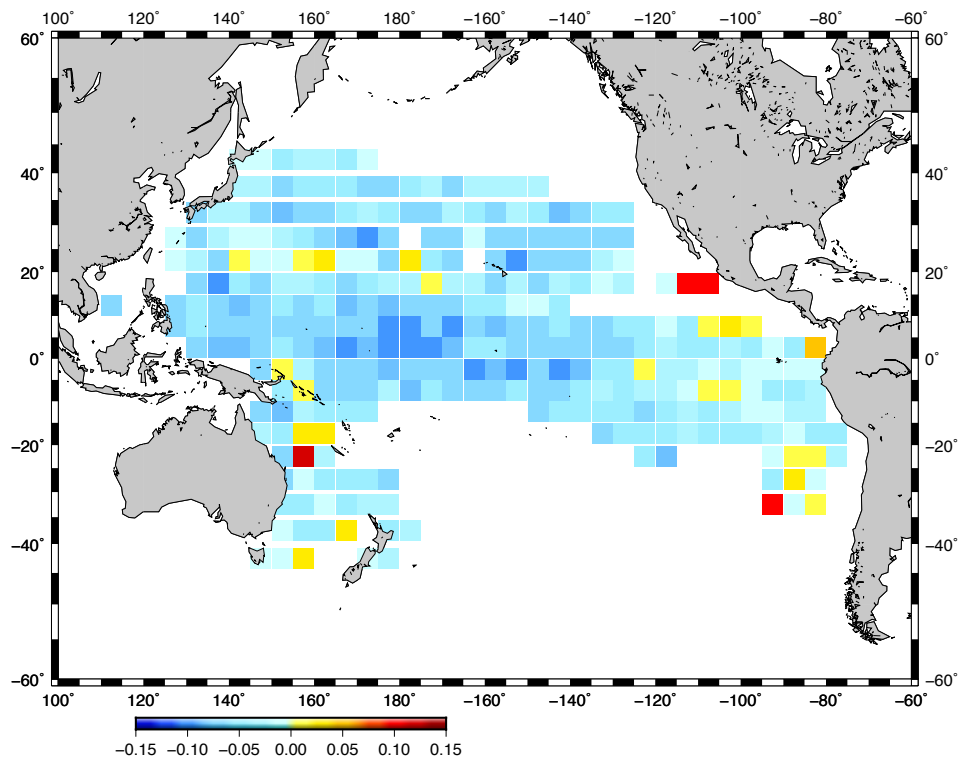
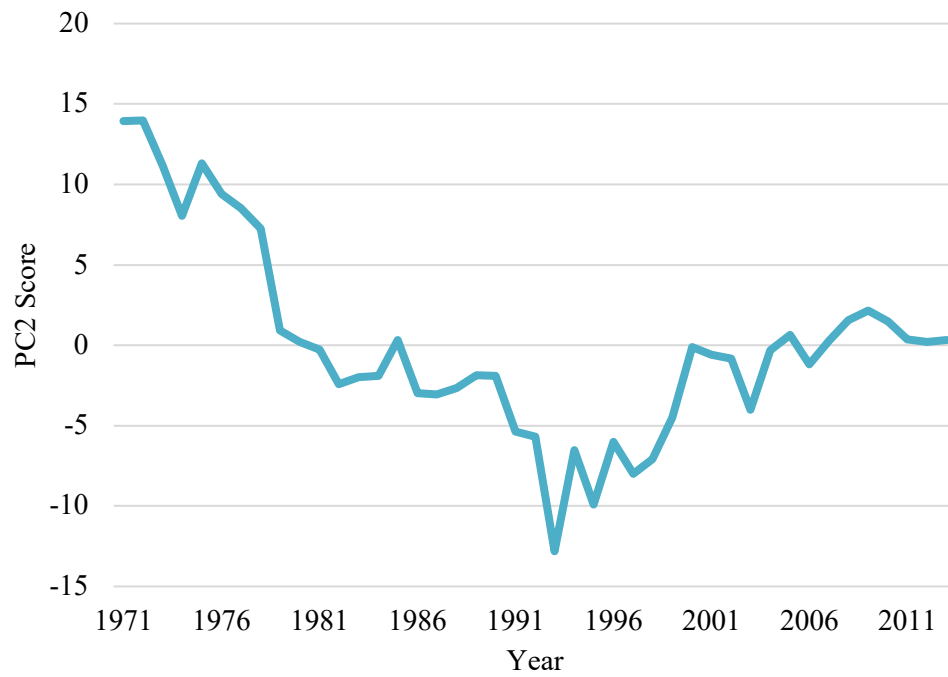


Figure 11. PC1 of CPUE of the yellowfin tuna from 1971 to 2013

(a) Annual PC1 score (b) PC1 eigenvector distribution

(a)



(b)

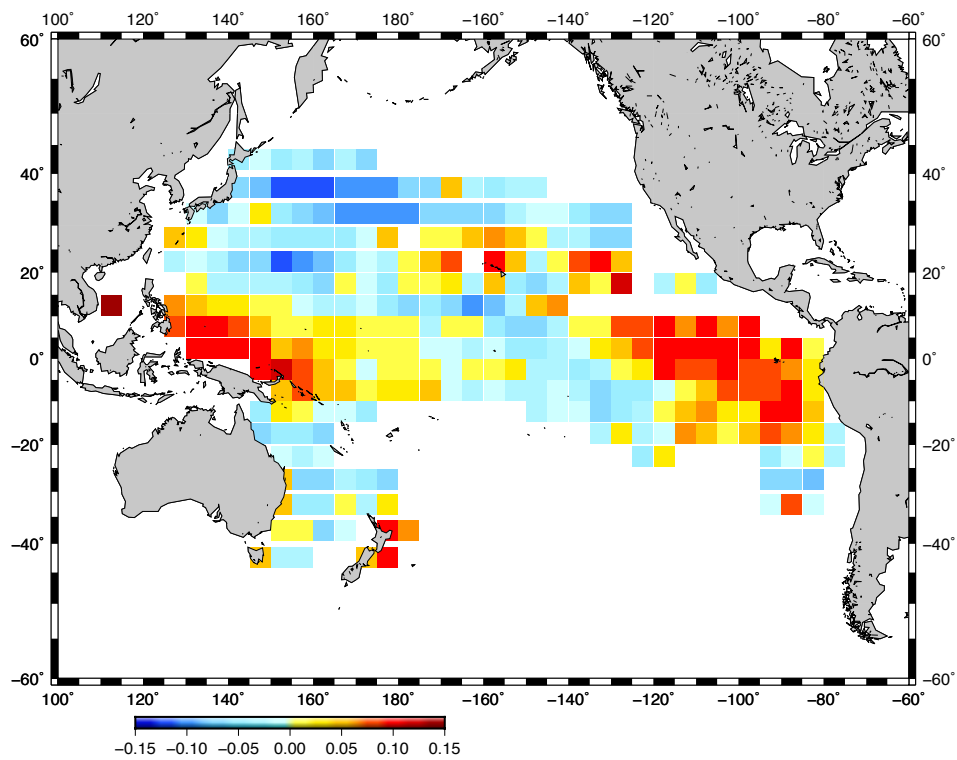
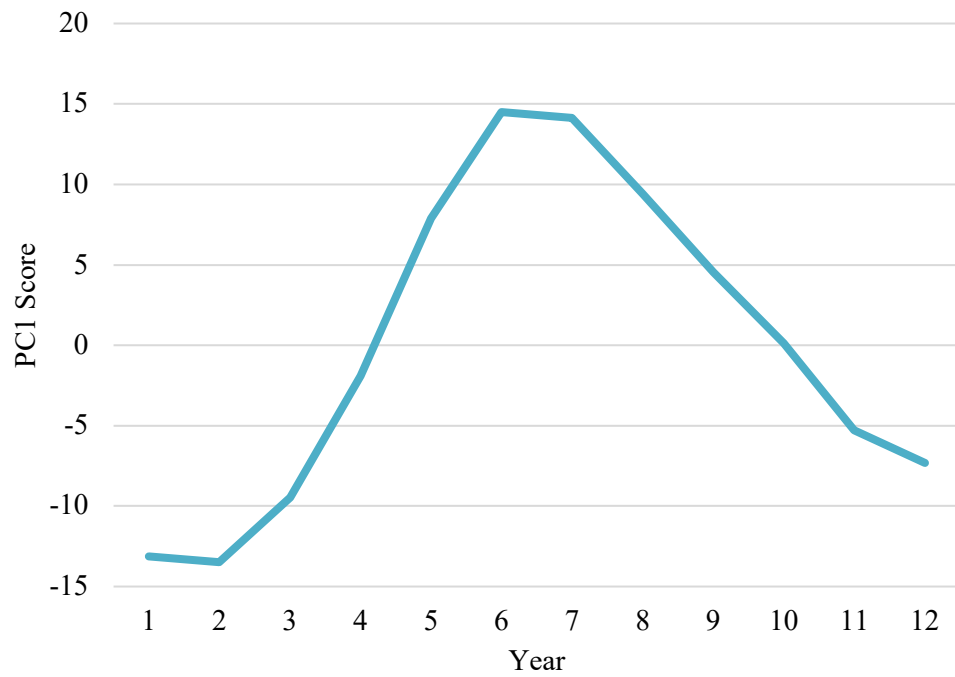


Figure 12. PC2 of CPUE of the yellowfin tuna from 1971 to 2013

(a) Annual PC2 score (b) PC2 eigenvector distribution

(a)



(b)

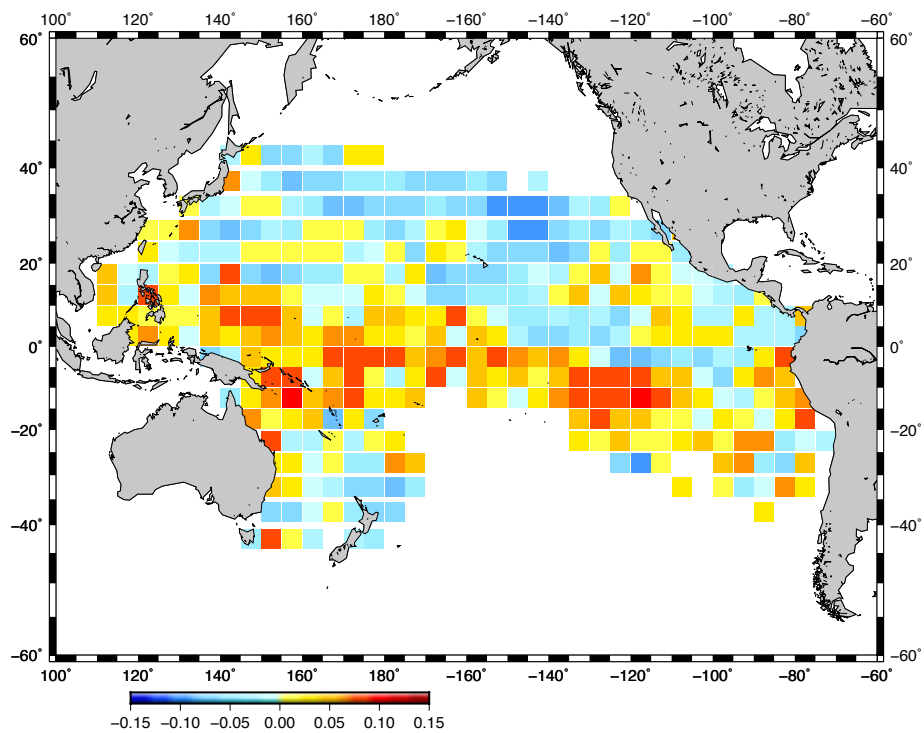
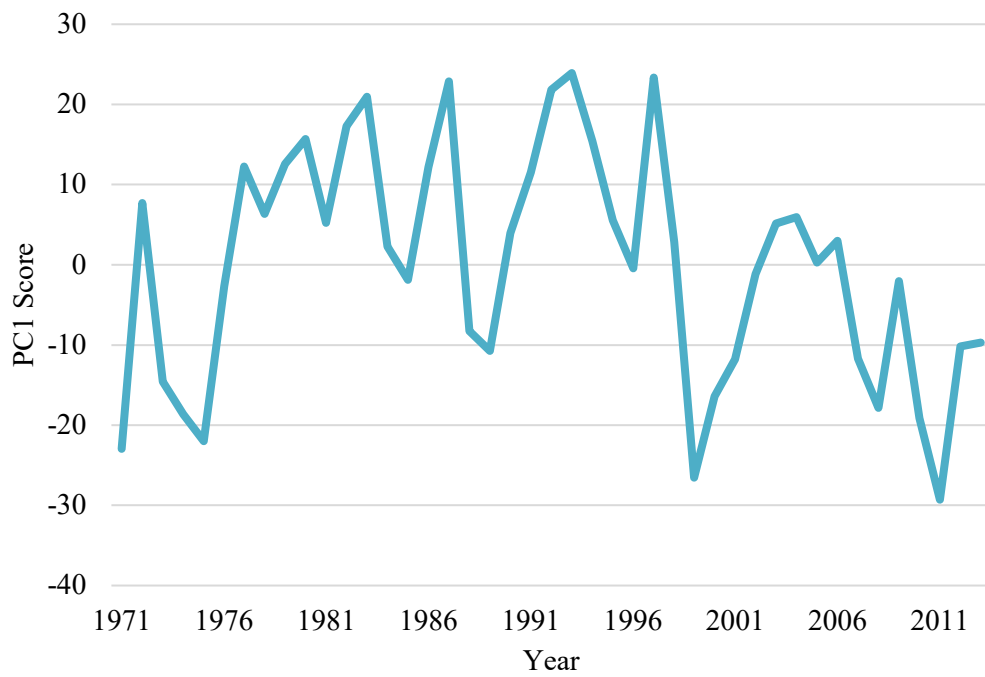


Figure 13. PC1 of monthly yellowfin tuna CPUE changes from 1971 to 2013

(a) Monthly PC1 score (b) PC1 eigenvector distribution

(a)



(b)

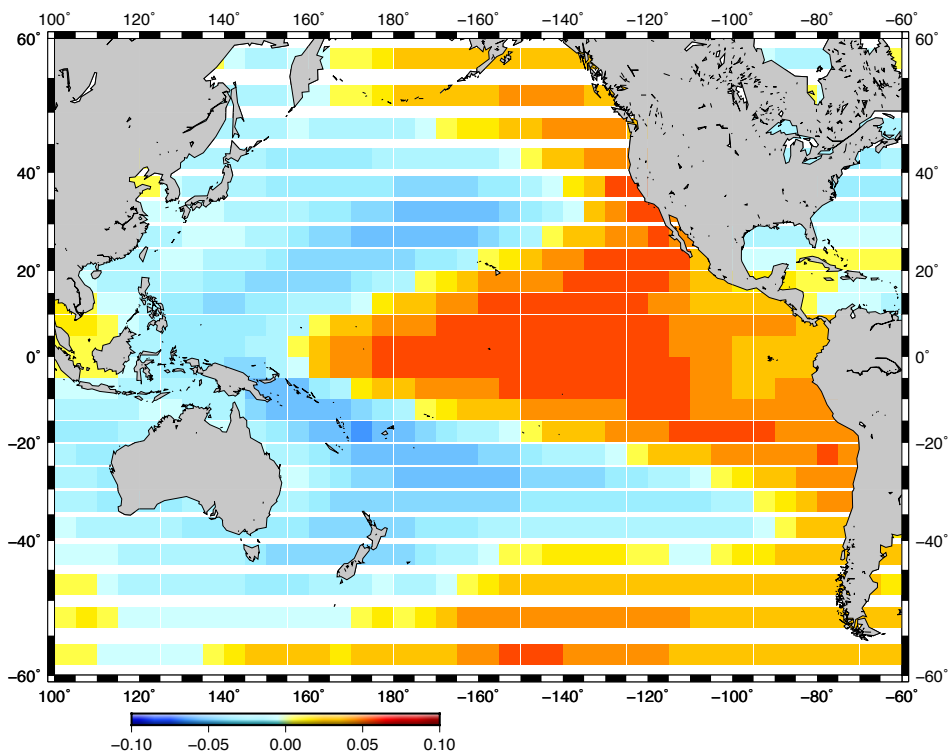


Figure 14. PC1 of annual changes in SST from 1971 to 2013

(a) Annual PC1 score (b) PC1 eigenvector distribution

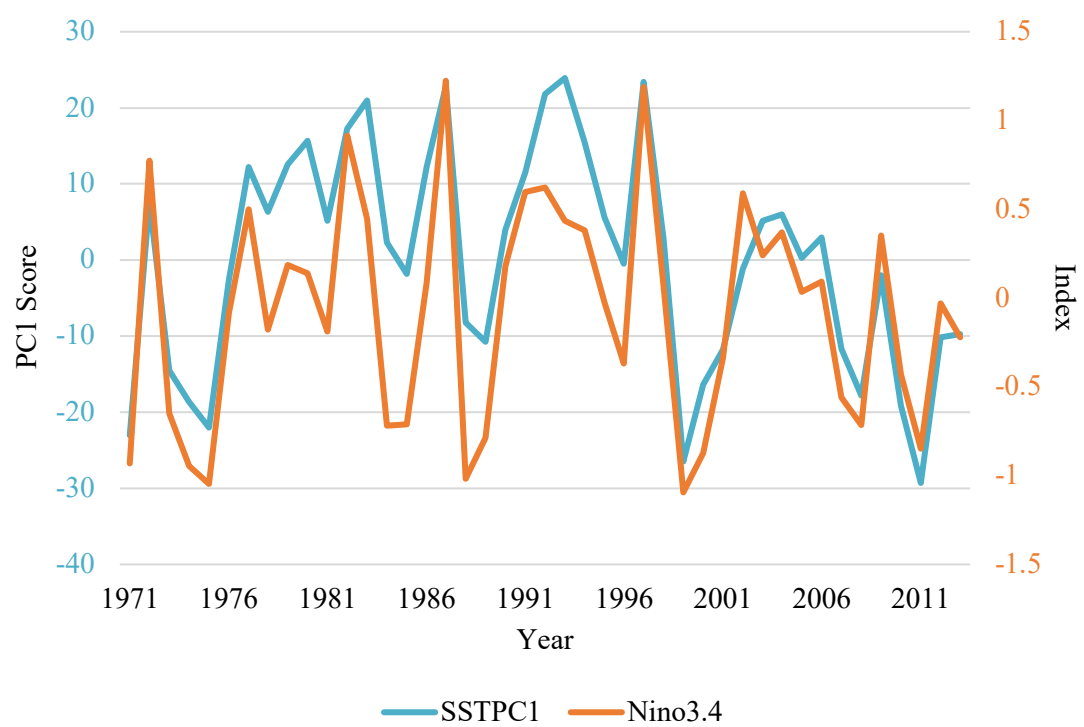
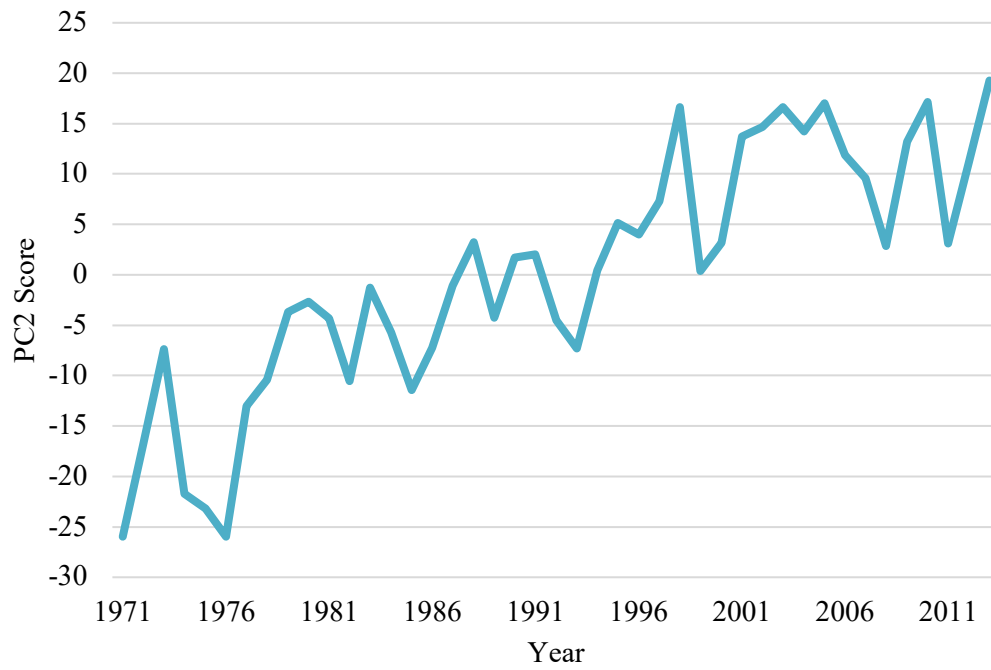


Fig.15 Correlation between SST PC1 and the Nino 3.4 index

(a)



(b)

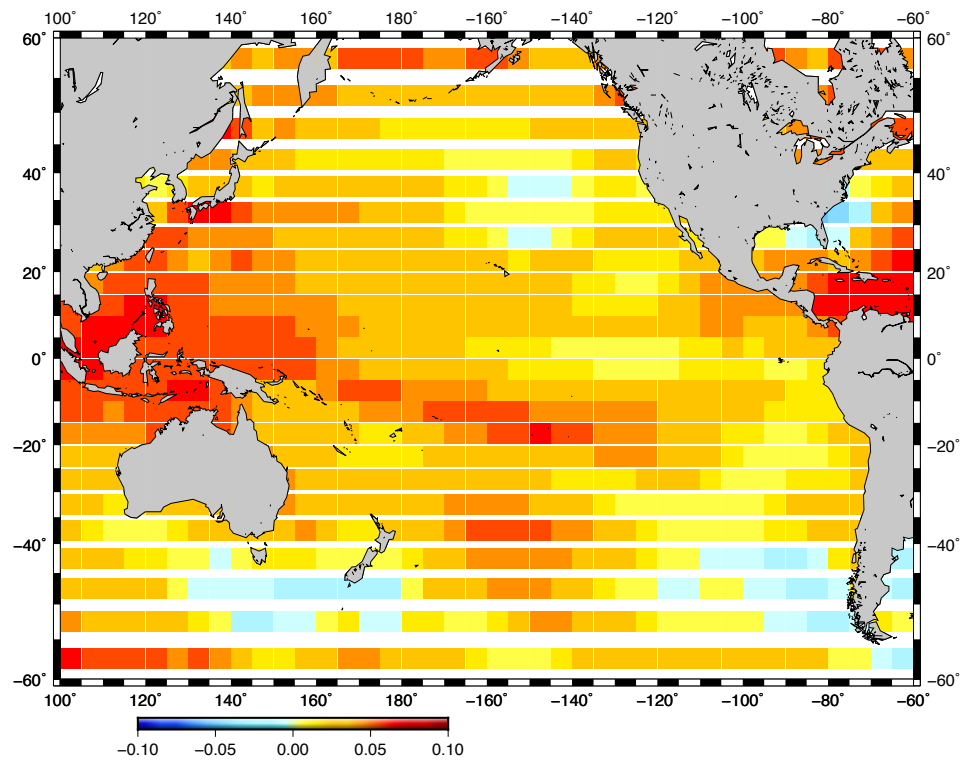


Figure 16. PC2 of annual changes in SST from 1971 to 2013

(a) Annual PC2 score (b) PC2 eigenvector distribution

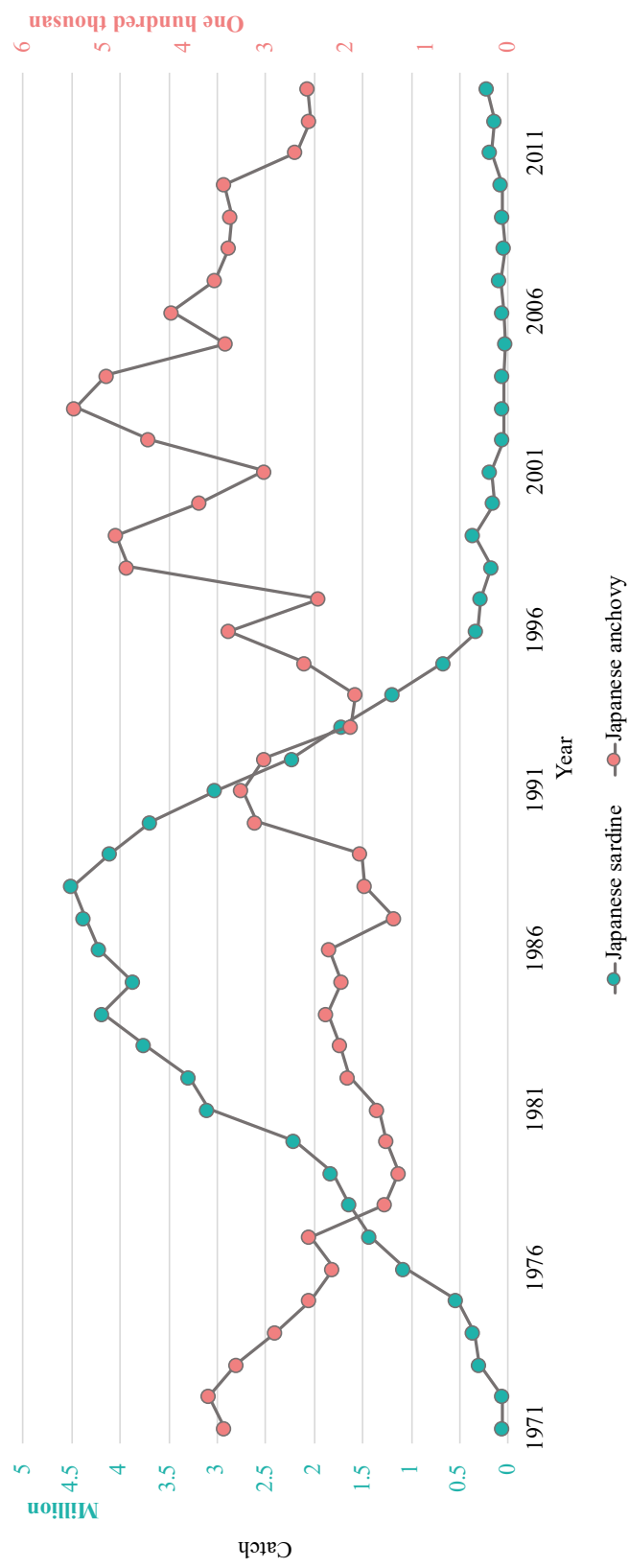


Fig.17 Annual catch change of Japanese sardine and Japanese anchovy

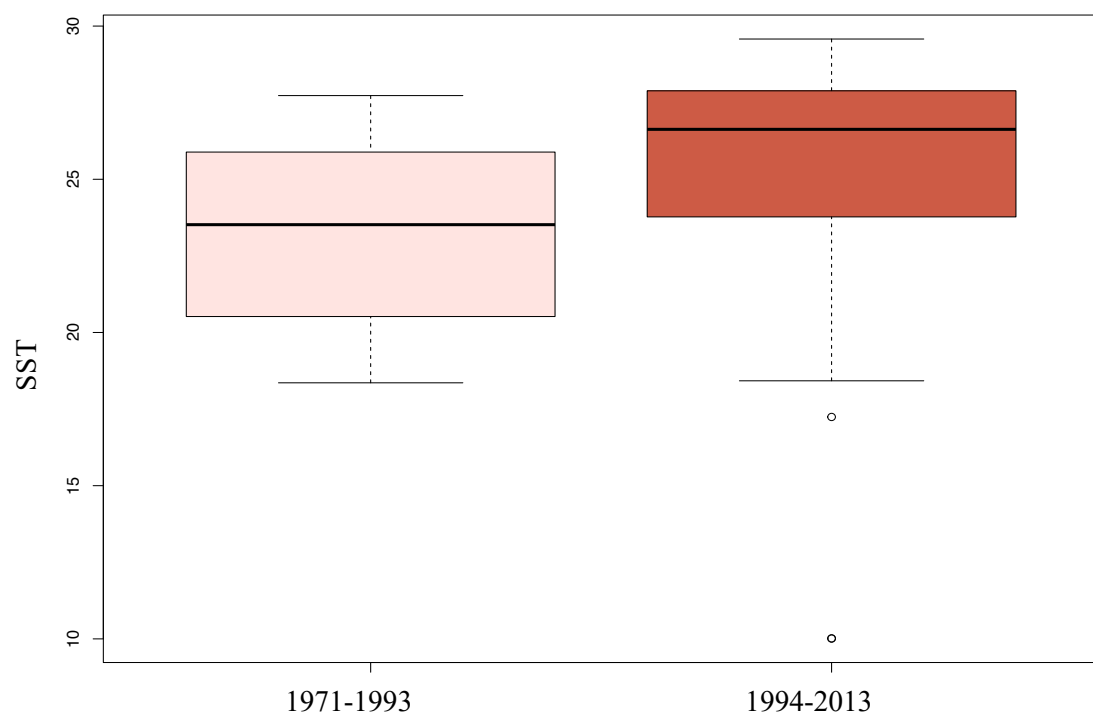
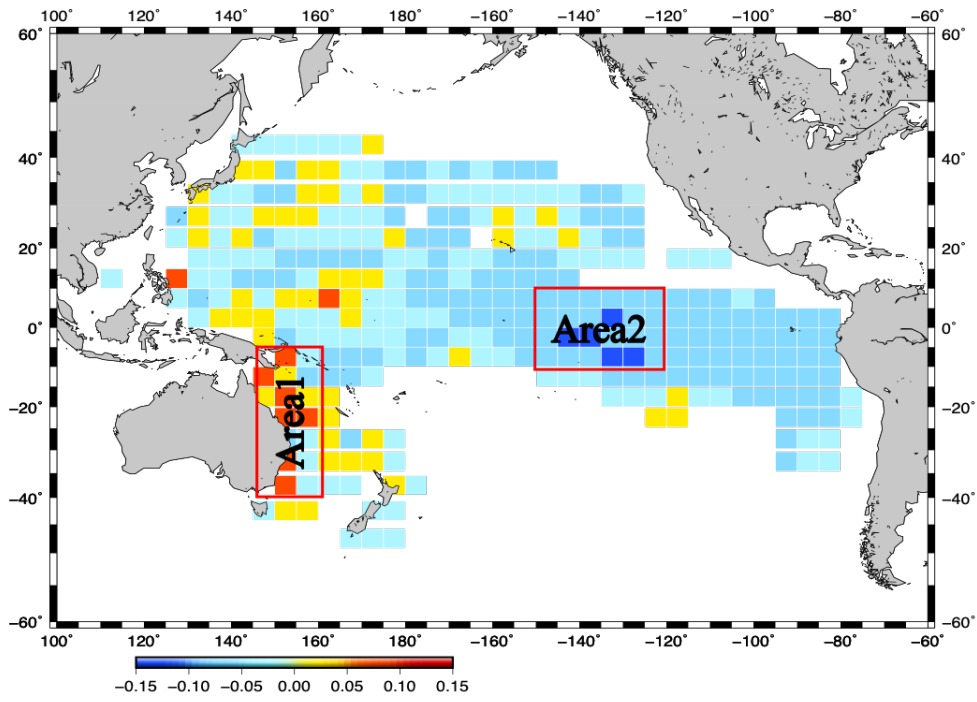


Fig.18 SST differences in high CPUE areas between 1971-1993 and 1994-2013

(a)



(b)

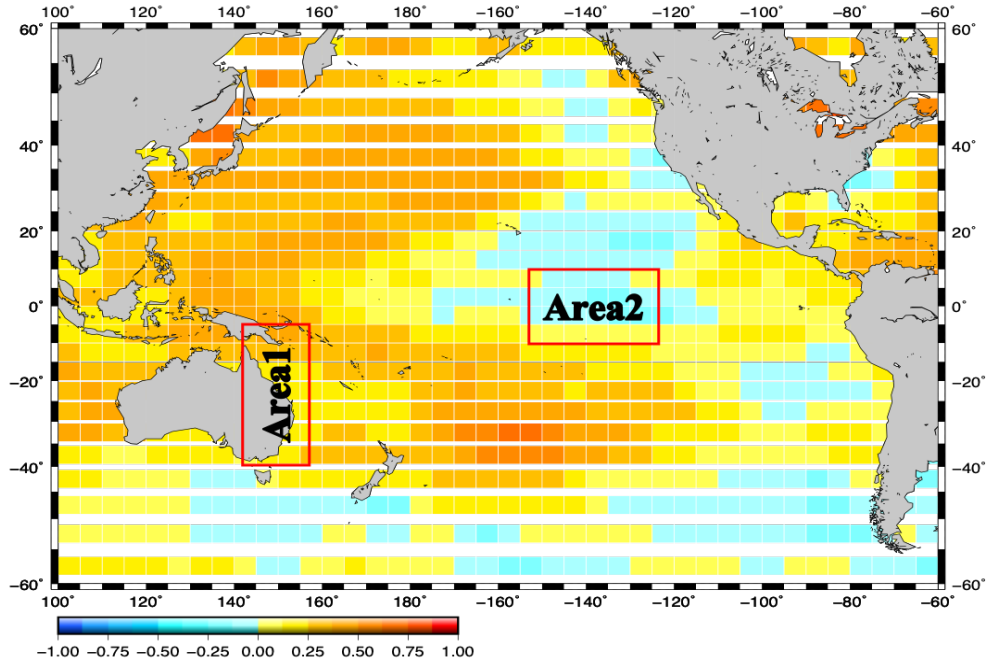


Figure 19. (a) Area1 (where positive eigenvectors of PC1 of the bigeye tuna were concentrated) and Area2 (where negative eigenvector of PC1 of the bigeye tuna were concentrated)
(b) SST difference in Area1 and Area2 between 1971-1993 and 1994-2013

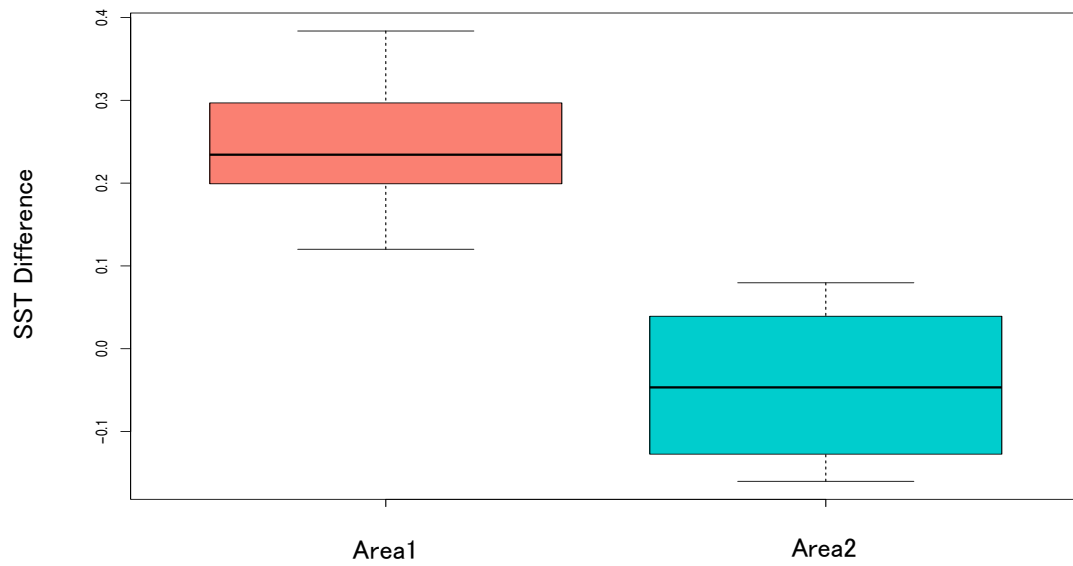


Figure 20. SST difference in Area1 and Area2 between 1971-1993 and 1994-2013

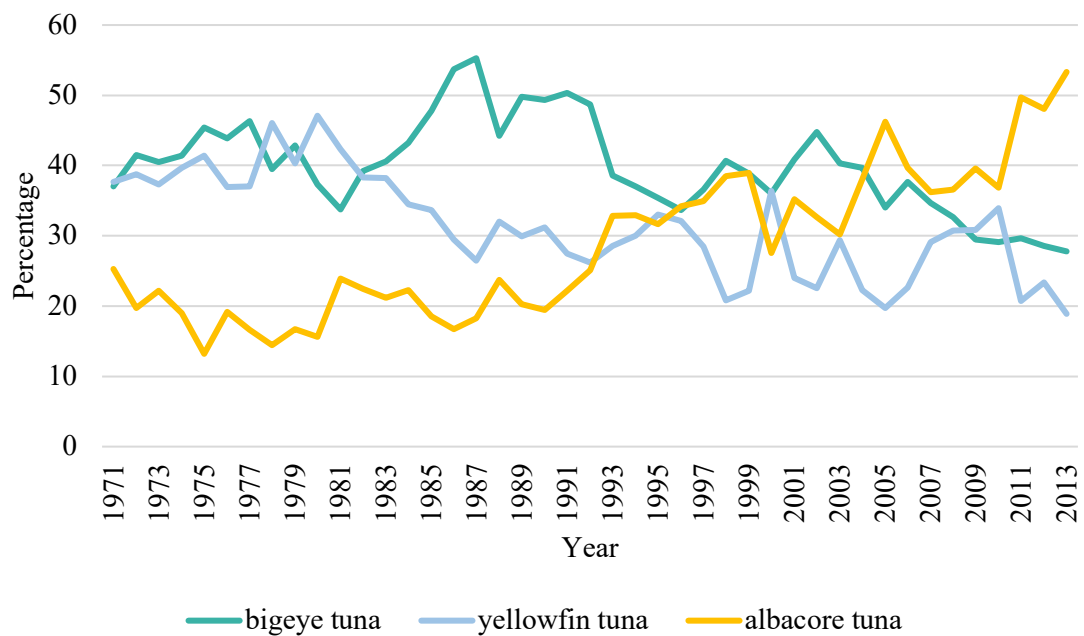


Figure 21. Annual percentage changes of catch numbers of the bigeye tuna, yellowfin tuna and albacore tuna caught by the Japanese longline fishery