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Variations in the abundance of Pacific saury (*Cololabis saira*) from the northwestern Pacific in relation to oceanic-climate changes

Yongjun Tian*, Tatsuro Akamine, Maki Suda

Fisheries Biology and Ecology Division, National Research Institute of Fisheries Science, Fisheries Research Agency (FRA), Kanazawa-ku, Yokohama 236-8648, Japan

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Abstract

Effects of oceanic-climate changes on the abundance of Pacific saury (*Cololabis saira*) in the northwestern Pacific during the last half century were investigated. Abundance indices of both large and medium size groups exhibit interannual–decadal variations, but their patterns were different. The large and medium size groups of saury are corresponding to the recruitments of winter- and spring-cohort, respectively. The abundance of large size group saury was significantly correlated with the winter sea surface temperature (SST) in the Kuroshio region, whereas the medium size group saury showed high correlations with SST in the Kuroshio–Oyashio transition zone and the Oyashio region, indicating that the two size groups are affected by subtropical and subarctic environment, respectively. Significant negative correlation between the abundance index and the southern oscillation index (SOI) suggested that El Niño-southern oscillation (ENSO) events have marked impacts on the large size group saury. Subtropical high pressure index and far east zonal index also show high correlations with the abundance of both large and medium size group saury, indicating a linkage between large-scale atmospheric circulation and the abundance of saury. These correlations demonstrate that the abundance of Pacific saury is directly affected by the SST fields through large-scale atmosphere–ocean interactions from the equatorial Pacific to mid- and high-latitude areas such as El Niño events.

Keywords: Pacific saury; Abundance; Decadal variation; Climate change; Sea surface temperature; El Niño

1. Introduction

Pacific saury (*Cololabis saira*) is widely distributed in the northwestern Pacific, and is one of the most important pelagic species taken by Japanese, Russian and Korean fisheries. Pacific saury exhibits large interannual variations both in abundance and size composition (Fukushima, 1979). Fig. 1 showed the annual catches and CPUE (in tons per haul) of saury based on the data from Tohoku National Fisheries Research Institute of Japan. Annual catches of saury in Japan have fluctuated greatly from 572,000 t in 1958 to 63,000 t in 1969 with an annual average of about 257,800 t over the past 51 years. The total catch of saury in 1998 dropped to 141,000 t which is less than half of that for the previous year.

Pacific saury makes extensive migrations from the subtropical to the subarctic region throughout the Kuroshio–Oyashio transition zone (TZ) which has complex oceanic structures (Fukushima, 1979). Pacific saury start the northward migration in spring, feed on plentiful foods in the Oyashio region during the summer and are fished during their southward migration off the northeast coast of Japan (Fig. 2). The spawning

* Corresponding author. Tel.: +81-45-788-7638; fax: +81-45-788-5001.
E-mail address: yjtian@fra.affrc.go.jp (Y. Tian).

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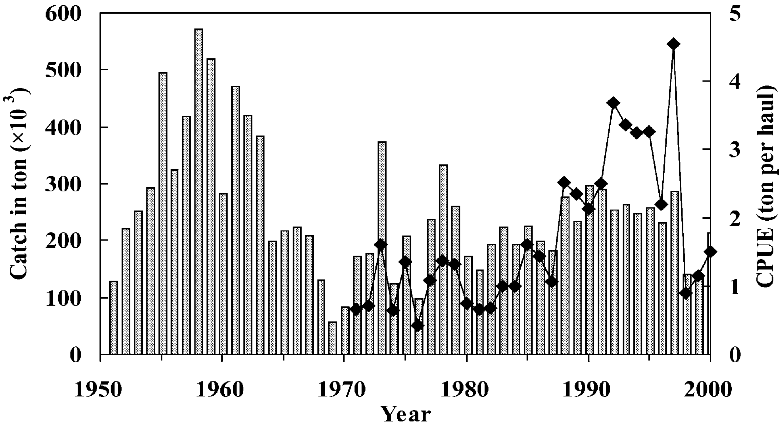

Fig. 1. Annual catches (vertical bars) in ton during 1951–2000 and CPUE (solid line) in ton per haul from 1971 to 2000 for Pacific saury in Japan.

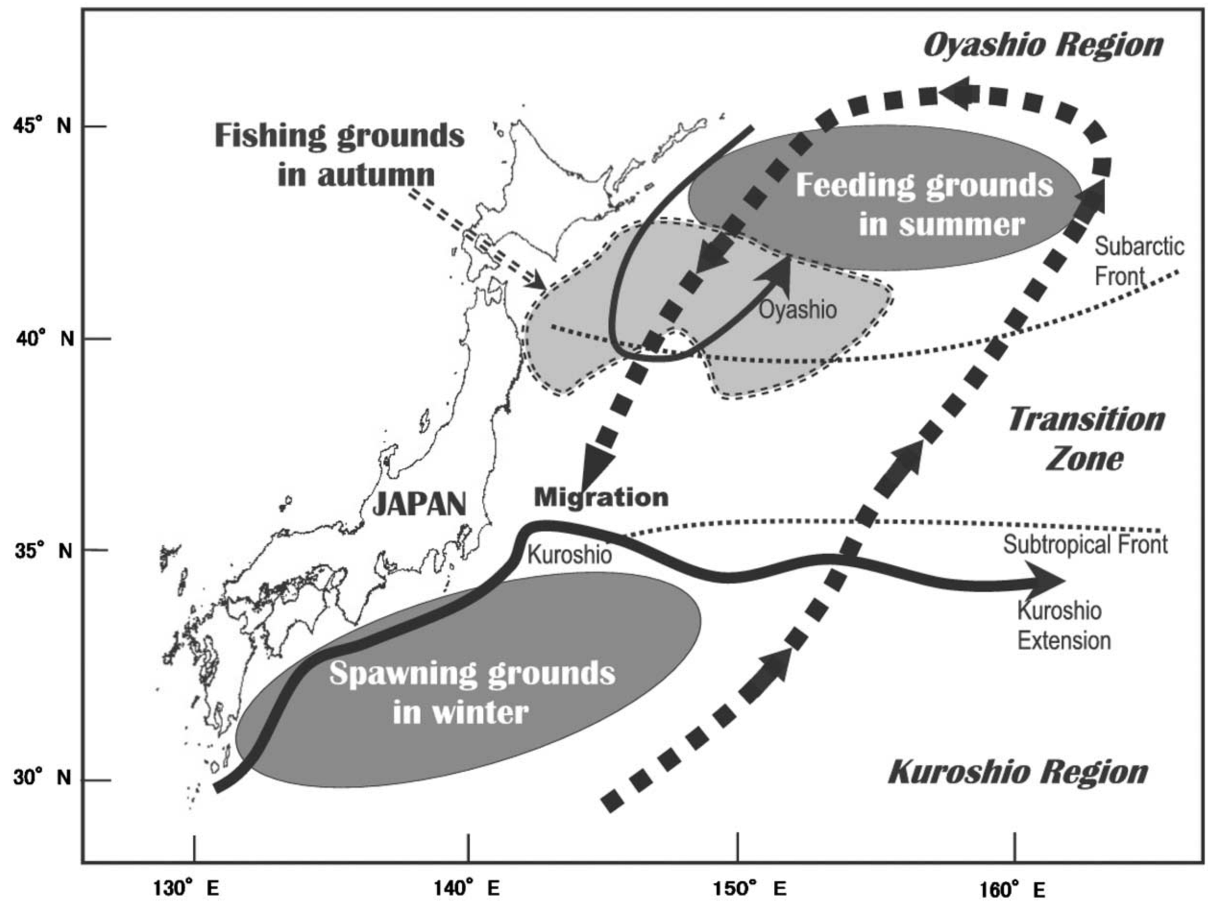

Fig. 2. Schematic diagram showing habitats of Pacific saury with oceanographic features along the Pacific coast of Japan.

season of Pacific saury continues from autumn through spring, shifting spawning grounds from the TZ to the Kuroshio region (Watanabe et al., 1997). The saury population in the northwestern Pacific is composed of three cohorts: winter-cohort spawning in the Kuroshio region, spring- and autumn-cohorts spawning in the TZ. Larval growth and survival rates of the saury largely vary with spawning cohorts, suggesting strong effects of oceanic conditions (Watanabe et al., 1997). The location and size of saury fishing grounds largely depend on the oceanographic conditions (Yasuda and Watanabe, 1994). Impacts of oceanographic conditions on the population dynamics of the saury are poorly understood. Matsumiya and Tanaka (1978) pointed out that the abundance of saury is seriously affected by reproductive success or failure, and drastic population decline does not result from overfishing. In fact, despite a descending trend in fishing efforts in the 1990s, both the catch and CPUE of saury have experienced an abrupt decline in 1998 from an abundant period (Fig. 1), indicating a strong influence of environmental factors on the trend of abundance (Ebisawa and Sunou, 1999; Tian et al., 2002).

There is increasing evidence that variations in the abundance of pelagic fishes are forced, either directly or indirectly, by changes in oceanic and climate environment (e.g. Sinclair and Tremblay, 1985; Mantua et al., 1997; Beamish et al., 1999). Recent studies have also revealed that the North Pacific atmosphere–ocean system fluctuates with a decadal scale (Trenberth and Hurrell, 1995; Nakamura et al., 1997; Minobe and Mantua, 1999). The response of ocean ecosystems to oceanic regime shifts and long-term climate changes has caused great concern (Mantua et al., 1997; Sugimoto and Tadokoro, 1998; Zhang et al., 2000). Pacific saury has a short life-span of 1–2 years, therefore impacts of climate change on the abundance of saury should appear after a short time lag. The purpose of this study is to unravel the mechanisms whereby the variability in climate and oceanic conditions is linked to the population dynamics of Pacific saury. We selected the sea surface temperature (SST) and several climate indices to examine their effects on saury abundance. We attempt to demonstrate that the abundance of Pacific saury is directly forced by interannual–decadal variations in the SST fields through large-scale atmosphere–ocean interactions from the equatorial to the mid-latitude region in the North Pacific.

2. Data and methods

2.1. Abundance index

Saury catch in number of fish with length composition in 1 cm interval from 1951 to 2000 was provided from Tohoku National Fisheries Research Institute of Japan. The saury catch has been divided into three size categories for the sake of convenience since 1951, and the catch in number of fish by size category is an effective abundance index for saury (Matsumiya and Tanaka, 1976; Oozeki et al., 1998; Kosaka, 2000). Despite the large interannual fluctuations in length compositions, two peak modes corresponding to the large and medium size saury clearly occur in size compositions for most years. Analysis of the length composition showed that the large and medium size saury are distinguished as two groups, indicated that the population of Pacific saury is dominated by two cohorts corresponding to the large and medium size groups (Matsumiya and Tanaka, 1974; Kosaka, 2000). Here we performed length frequency analysis (LFA) for catch data of saury from 1951 to 2000, and use the estimated catch in number of fish by size group as the abundance index. Because the size group estimated from LFA represents the age composition and year-class strength, the abundance index by size group was supposed corresponding to different spawning cohort. The saury achieves 30 cm in body length within 10 months (Watanabe et al., 1988), therefore most of the catch consists of the recruitment of the current year class. CPUE is a good index of saury abundance in weight but only available after 1971 (Ebisawa and Sunou, 1999; also see Fig. 1). Accordingly, the abundance index of the large and medium size group could be a good index representing the year-class strength or recruitment compared with the catch in weight and CPUE.

2.2. Sea surface temperature

A SST data set for the northwestern Pacific was provided from the Japan Meteorological Agency (JMA). The JMA data set is made up of 10-day-averaged SST in 1° grid (latitude × longitude) over the northwestern Pacific from 100°E to 180°E between equatorial to 60°N for the period from 1950 to 2000. Monthly mean SST from January 1950 to December 2000 was constructed by averaging the three times values of each month.

In this study, we use three area-averaged time series of monthly mean SST extracted from the above new data set to relate to the abundance index of Pacific saury. The three time series of SST for the Kuroshio region (28–35°N, 128–145°E), the TZ (35–40°N, 140–160°E) and the Oyashio region (40–45°N, 140–160°E), were calculated by averaging the grid means of each area. These three geographical areas generally cover the distribution and migration areas of Pacific saury, and almost corresponding to the spawning grounds in winter and spring, and feeding ground in summer, respectively (Fig. 2).

2.3. Climate indices

Southern oscillation index (SOI) and three atmospheric circulation indices (ACI) were used as climate indices from the equatorial Pacific to the high latitude area of the North Pacific to relate to the abundance index of Pacific saury. SOI is defined as the difference in sea level pressures between Darwin (Australia) and Tahiti (Trenberth, 1990). SOI used here is the standard monthly series of the standardised Tahiti data minus the standardised Darwin data; it was provided from the Climate Predictive Center of NOAA. The extreme negative (positive) values of SOI represent El Niño (La Niña) episodes. Linkage between the El Niño and southern oscillation (ENSO) has been recognised and the ENSO events have been shown having large effects not only on global climate changes, but also on the marine ecosystems (Sinclair and Tremblay, 1985; Tsai et al., 1997).

The ACIs were provided by JMA, they were calculated for monitoring the extra-tropical circulation in the north hemisphere using the 500 hPa height anomalies in 10° grids (Tomosada, 1993). Here we use three ACIs, which are the subtropical high pressure index (Sub High), the far east zonal index (R2-ZI) and the far east polar vortex index (R2-PV) from the subtropic to high-latitude region, to examine the effects of atmospheric circulation on Pacific saury. These three indices were used as monthly anomalies values available for the period from 1950 to 1999. Sub High is the zonal mean between 20°N and 30°N from 130°E to 170°E, and is associated largely with the weather conditions in Japan. R2-ZI is the zonal difference between 40°N and 60°N from 90°E to 170°E, it is an index representing the meandering as well as the position and intensity of the westerly jet in the mid-latitude, and is similar to the northern hemisphere zonal index (NHZI) used by Sugimoto and Tadokoro (1998). R2-PV is the zonal mean between 70°N and 80°N from 90°E to 170°E, representing the position and strength of the polar vortex in the high-latitude. Sub High, R2-ZI, and R2-PV are generally used as climate indices of subtropic, subarctic and polar regions, respectively. Several studies have shown that variations in oceanic conditions and zooplankton biomass in the coastal waters of northeast Japan are linked with these ACIs (Tomosada, 1993; Tomosada and Odate, 1995; Sugimoto and Tadokoro, 1998).

2.4. Correlation and trend analysis

The cumulative sum (CuSum) of the anomalies for time series data was used to examine the trend in the index. The method of CuSum is a simple addition of a datum to the sum of all previous data points (Beamish et al., 1999). The CuSum graph provides a visual picture to study the trend in a time series. We also carried out correlation analysis to evaluate quantitatively the effects of oceanic and climate changes on the saury, and to investigate the linkages between the climate and oceanic indices.

3. Results

3.1. Interannual–decadal variations in the abundance

Over the past 50 years after 1951, mean lengths of saury catch from LRA ranged from 24.0 to 28.5 cm (with mean of 26.8 cm) for the medium size group and from 28.9 to 32.4 cm (with mean of 30.7 cm) for the large size group, respectively (Table 1). The abundance index has shown large interannual variations ranging from 0.21 to 4.18 for the medium size group and from 0.03 to 2.38 for the large size group (in number of billion fishes), but their trends are different (Fig. 3). The abundance of large size group saury increased during the period from 1954 to 1962, decreased sharply from 1963 to 1976 (a great recovery in 1973), sustained a relatively stable period from 1977 to 1987, and

Table 1
Summary of the size composition and abundance index Pacific saury estimated from LFA during 1951–2000

Size group	Fish length (cm)			Abundance index (billion fishes)		
	Range	Mean	S.D.	Range	Mean	S.D.
Medium	24.0–28.5	26.8	1.1	0.21–4.18	1.50	0.91
Large	28.9–32.4	30.7	0.7	0.03–2.38	0.88	0.61

increased rapidly during 1988 to 1997. This pattern strongly indicates decadal-scale variations together with large interannual fluctuations in the abundance. There are clear changes around in 1953, 1963, 1972, 1977, 1982, 1987 and 1997 in the trends. For medium size group saury, there has been a drastic increase until 1963, after that a declining trend has been continuing. Decadal-scale variations in the abundance of medium size group saury also occurred during 1951–1963, 1964–1976, 1977–1987 and 1988–2000. The variation patterns for medium size group saury are almost similar to that of large size group saury until 1976. After 1977, however, particularly after 1987, the patterns are completely opposite to large size group, indicating variations in the abundance for the two size groups are different and may be affected by different oceanic systems. We can identify changes around 1964, 1976 and 1987 for medium size group saury.

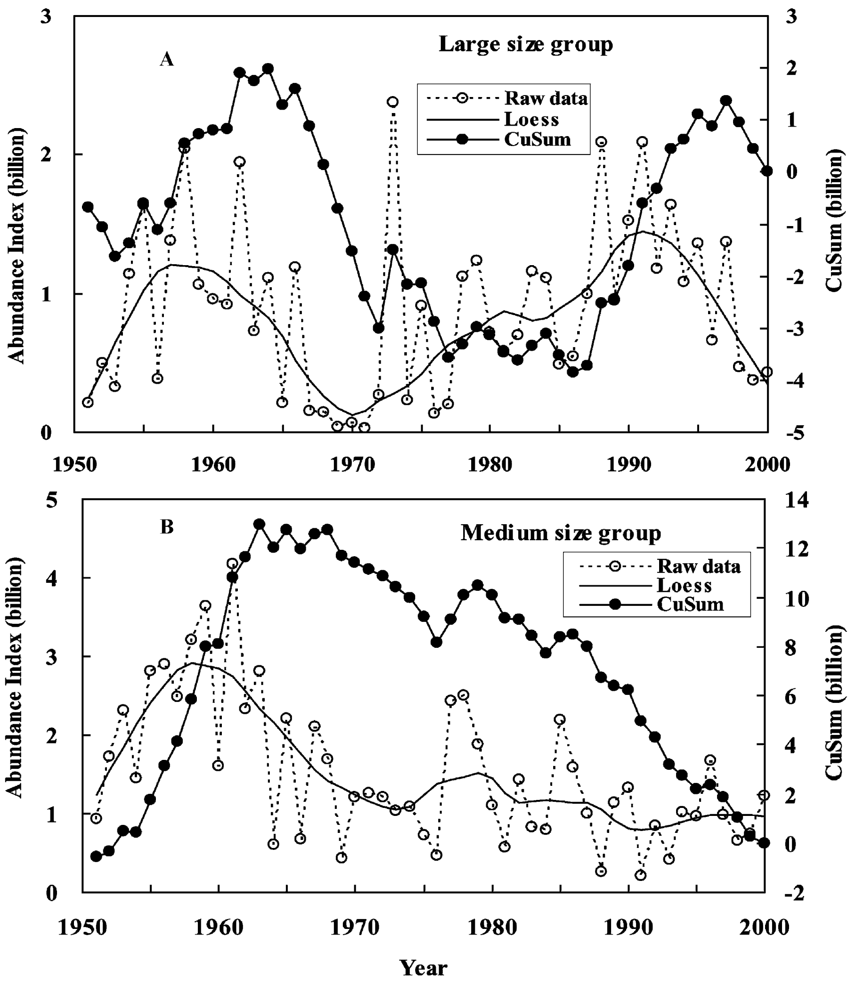

Fig. 3. Raw data (broken line with open circles) and cumulative sums (CuSum: solid line with solid circles) of the abundance index by size group for Pacific saury from 1951 to 2000. The solid line is the LOESS smoother with a band width of, *f*, 0.20.

3.2. SST and abundance index

SSTs showed large differences between oceanic regions. Averages of annual mean SST during 1950–2000 are 23.0 °C (with variance of 7.0%) in the Kuroshio region, 17.8 °C (with variance of 23.6%) in the TZ and 9.9 °C (with variance of 21.0%) in the Oyashio region, respectively (Fig. 4A–C). All of annual mean SST for these three areas exhibit large interannual variations, but variations in the TZ and

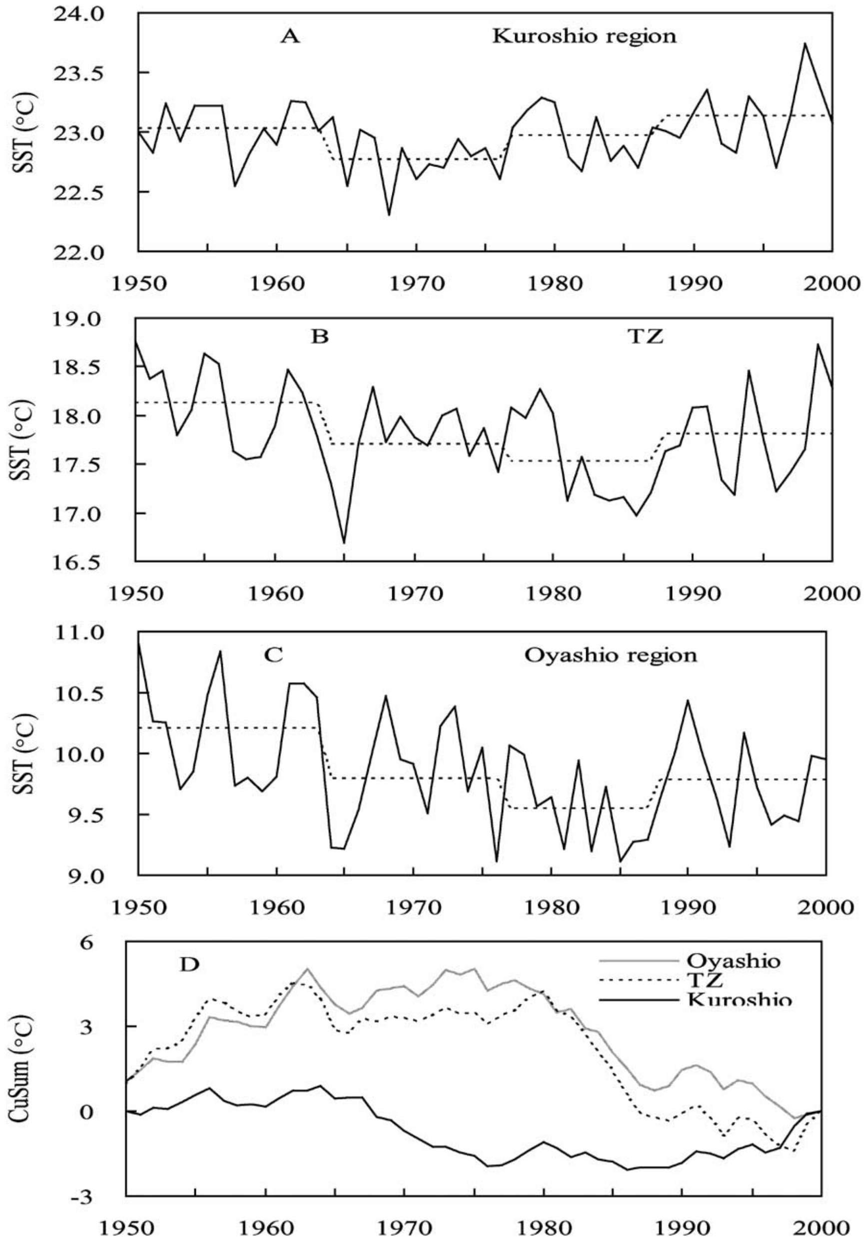

Fig. 4. Time series of annual mean SST for three oceanic regions (A–C) and their cumulative sums of the anomalies (CuSum: D). (A) The Kuroshio region, (B) The Kuroshio–Oyashio TZ, (C) The Oyashio region. Dotted lines in (A)–(C) indicate the decadal means of 1950–1963, 1964–1976, 1977–1987 and 1988–2000.

Oyashio region are larger than that in the Kuroshio region. There has been a long descending trend with large annual variations for annual mean SSTs in the TZ and Oyashio region from 1950 to 1986, while an ascending pattern is clear in the Kuroshio region after the 1970s. Variation patterns in the SSTs for the TZ and Oyashio region are similar, but are different with that in the Kuroshio region, indicating two different oceanic systems occur affecting the Kuroshio and the Oyashio regions. The CuSum graphs showed distinct decadal variation patterns for the period almost during 1950–1963, 1964–1976, 1977–1987 and 1988–2000 (Fig. 4D). The decadal mean is highest in the 1990s for the Kuroshio region, while it is lowest during 1977–1987 for the TZ and Oyashio region, indicating two different patterns in the SST fields.

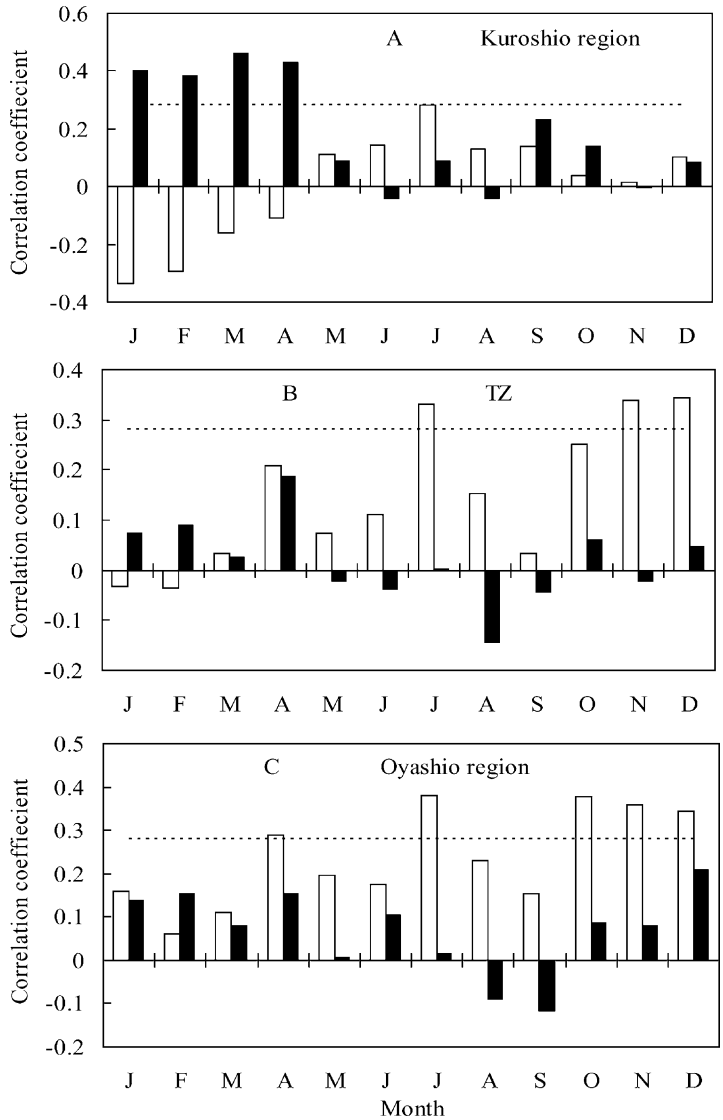

Fig. 5. Correlation coefficients between abundance index of Pacific saury and SST by water. (A) The Kuroshio region, (B) The Kuroshio–Oyashio TZ, (C) The Oyashio region. Black and white bars represent large and medium size group saury, respectively. Dotted lines represent significant at $P = 0.05$.

Correlations between the abundance indices of saury and the monthly mean SSTs showed that the abundance of large size group is significantly correlated with the SSTs in the Kuroshio region during January–April (Fig. 5). In particular, large size group saury showed a good correspondence with winter (January–March) SSTs in the Kuroshio region on interannual–decadal scales (Fig. 6), correlation between the winter SST in the Kuroshio region and the abundance index of large size saury is significant at the 99% level ($r = 0.47$, $P < 0.01$). For the medium size group saury, the abundance index significantly correlated with the SST in the TZ in July and with the SST in the Oyashio region in July and during autumn from October to December. Months in which the SSTs showed high correlations with medium size group saury are generally consistent with the period when the medium size group saury migrated in the TZ.

It is notable that the trends of the large and medium size saury correspond with the SST in the Kuroshio region and with the SST in the TZ and Oyashio region, respectively, demonstrating that the SST fields have a large effect on the trend of abundance of Pacific saury. It suggested that the abundance of large size group saury are affected only by the SSTs in the Kuroshio region during the winter season from January to April, whereas the medium size group saury were largely associated with SSTs in the TZ and Oyashio region during summer and autumn with an extensive and long range both in time and space.

3.3. SOI and abundance index

The annual mean SOI showed large interannual variations (Fig. 7A). A distinct change occurred in 1976, from this year the pattern of SOI changed from positive to negative anomalies. Because the strong

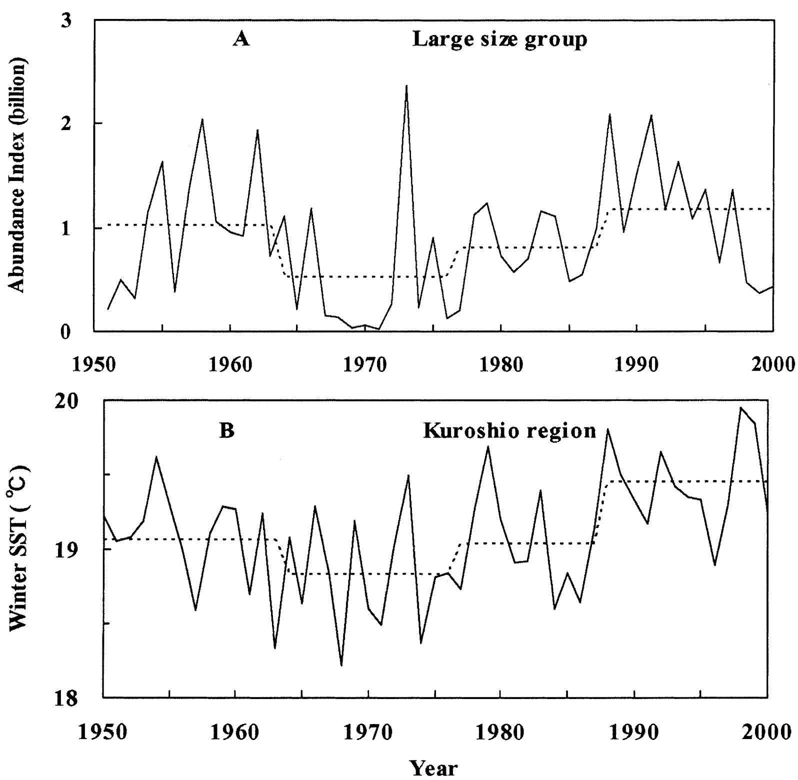

Fig. 6. Time series of abundance index of the large size group saury (A) and winter SST in the Kuroshio region (B). Dotted lines indicate the decadal means of 1950–1963, 1964–1976, 1977–1987 and 1988–2000.

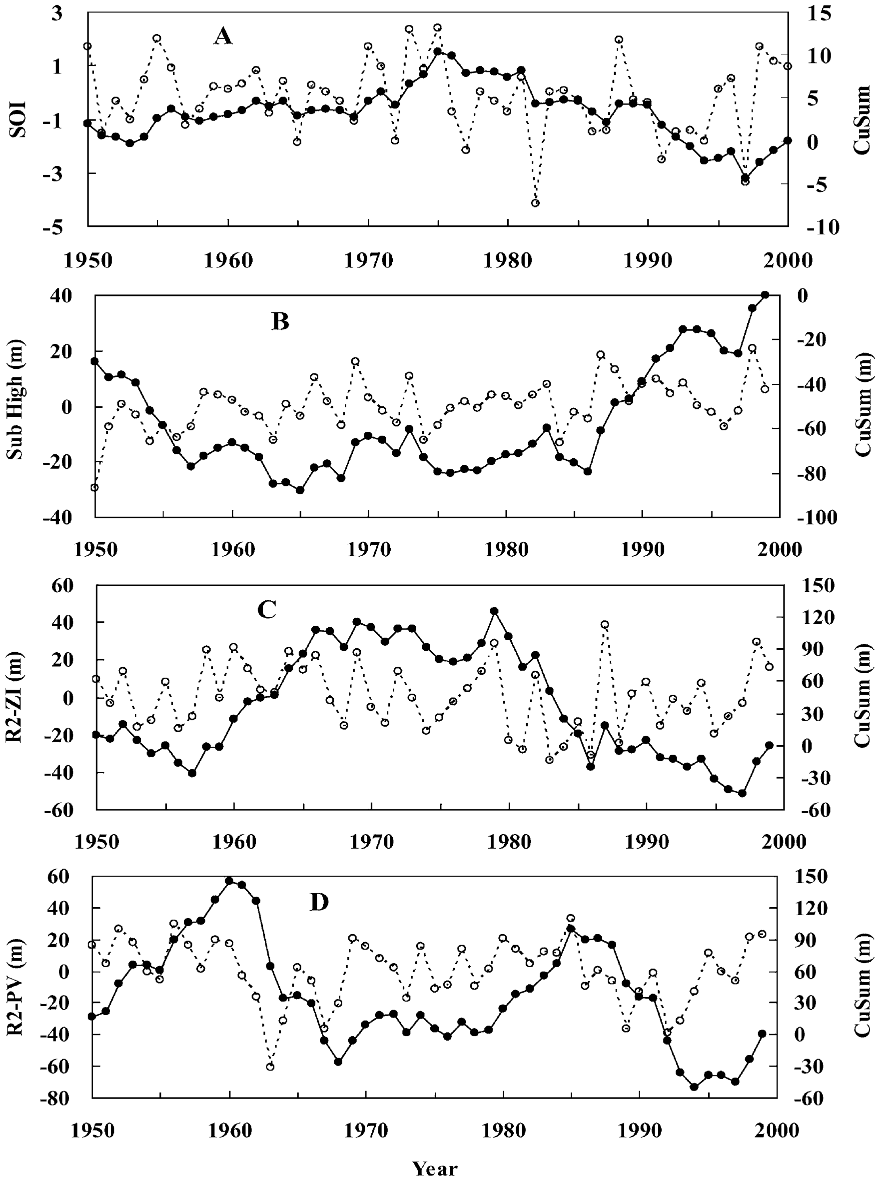

Fig. 7. Anomaly values (open circles) and their cumulative sums (CuSum: solid circles) for the four climate indices. (A) SOI from 1950 to 2000, (B) subtropical high pressure index (Sub High) from 1950 to 1999, (C) far east zonal index (R2-ZI) from 1950 to 1999, (D) far east polar vortex index (R2-PV) from 1950 to 1999.

negative (positive) SOI represents El Niño (La Niña) episodes, it seems that El Niño trends tend to be intense after 1977, particularly during 1990–1995, while La Niña trends are evident until 1976.

The abundance index of large size group saury showed a high correlation with SOI from June in the previous year to February of the following year (Fig. 8). In particular, SOI during the summer and autumn of the previous year in the north hemisphere, in which period the El Niño episode was often in the developing phase, have a negative significant correlation with the abundance of large size saury. This

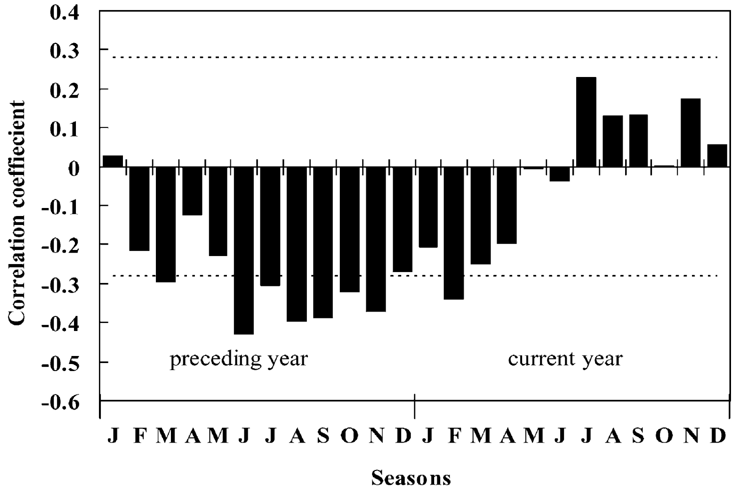

Fig. 8. Cross-correlation between the abundance index of large size group saury and SOI. Dotted lines represent significant at $P = 0.05$.

demonstrated that El Niño (La Niña) has a positive (negative) effect on the abundance of the large size group saury.

Because ENSO events usually persist over 1 year, here we define an ENSO year as the value of SOI averaging during the ENSO development phase from June to November of less or larger than 1. Hence we selected 25 ENSO years including 15 El Niño (1951, 1953, 1957, 1963, 1965, 1969, 1972, 1977, 1982, 1987, 1991–1994, 1997) and 10 La Niña events (1950, 1955, 1956, 1964, 1970, 1971, 1973, 1975, 1988, 1998) over the past 51 years. The abundance index during El Niño (La Niña) years is higher (lower) than that during the normal years (Fig. 9). The mean of the abundance index during the El Niño years is about three times as that during the La Niña years, the difference in the abundance index between El Niño and La Niña years is significant at 99.9% confidence limit by a t-test ($t = 4.50$, $n = 23$, $P < 0.001$). This strongly indicates that both El Niño and La Niña events have

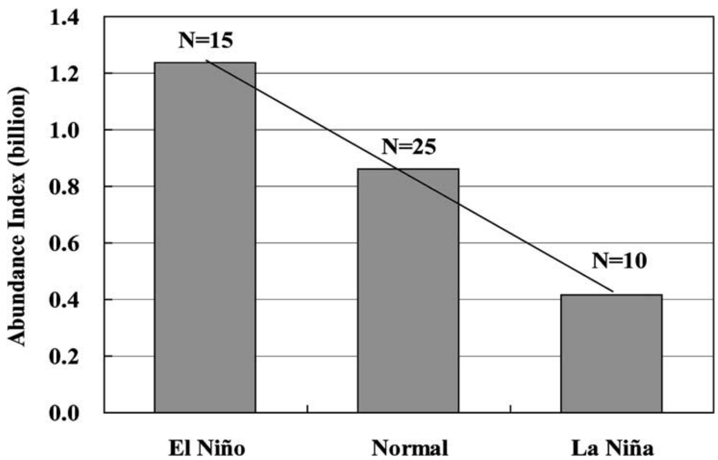

Fig. 9. Distribution of the abundance index for the large size group saury by ENSO events during 1950–2000. El Niño, La Niña and normal years are defined as $SOI \leq -1$, $SOI \geq 1$ and $-1 < SOI < 1$, respectively. There is 1-year lag between the abundance index and the ENSO (ENSO leading the abundance index). N represents the number of years.

great influences on the large size group saury with a lag of 1 year. It is worth to note that the abundant period during the 1990s for large size group saury corresponds closely with the long and strong El Niño trends, whereas the rare abundance from mid-1960s to the first half of 1970s occurred in strong La Niña years (Fig. 7A). We can also identify that abrupt changes in the trend of the abundance for large size group saury largely associated with the change in ENSO phase such as 1976–1977 and 1997–1998 (Fig. 3A).

On the other hand, there is no evident relationship between the abundance of medium size group saury and SOI, indicating that the influence of ENSO on the medium size group saury is limited.

3.4. ACI and abundance index

All the three ACIs show large interannual variations with distinct decadal variation patterns (Fig. 7B–D). Sub High showed an above-average period after 1987, indicating an intensive high pressure trend in the 1990s in the subtropics. R2-ZI shows an opposite trend with R2-PV generally.

The abundance index of large size group saury showed significant correlations with Sub High in January and September, while medium size group saury significantly correlated with the Sub High during June, July and October (Fig. 10), these different patterns indicate that Sub High has opposite effects on the large and the medium size saury. For R2-ZI and R2-PV, except for a significant positive correlation between medium size group saury and R2-ZI in July ($r = 0.33$, $P < 0.05$), no clear relation was identified between the two ACIs and saury abundance indices. This indicates that arctic circulation does not have evident effects on the large size group saury, while the medium size group saury may be affected by mid-latitude atmospheric circulation conditions during summer and autumn.

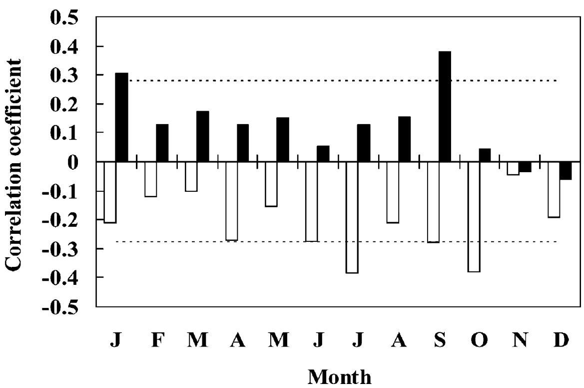

Fig. 10. Cross-correlation between Sub High and abundance index of Pacific saury by size group. Black and white bars represent the large and the medium size group saury, respectively. Dotted lines represent significant at $P = 0.05$.

4. Discussion

4.1. Mechanisms of population dynamics of Pacific saury

Interannual–decadal variations in the abundance of both large and medium size group saury strongly suggest the effects of oceanic and climate changes (Fig. 3). Synchronous patterns between the abundance index and SSTs demonstrated that the abundance of saury is directly forced by the SST fields in the spawning grounds (Fig. 5). Different variation patterns in the abundance for the two size groups and in SSTs by waters indicated that the large and medium size group saury are affected by two different oceanic systems. Response of the saury to SSTs suggested that the large and medium size group saury correspond to the winter- and spring-spawned cohorts, respectively. It demonstrated that the winter SSTs in the Kuroshio region strongly affect the early survival rates, and determine the recruitment success of the winter-spawned cohort. Spawning of the saury starts in September and continues until June, shifting locations from spawning grounds in the TZ and the Kuroshio region (Watanabe et al., 1997). Larvae and juvenile from the autumn-cohort spawning in the TZ should migrate to the Kuroshio region to overwinter, because of high mortality of saury larvae and the variable SSTs in the TZ (Watanabe et al., 1997). Recent study revealed that the spawning of saury in the Kuroshio region continues from autumn through spring with a peak in winter, and the winter cohort plays an important role in the recruitment (Kurita, 2001). Considering the long spawning season and migration patterns of saury, it is reasonable to regard the large (medium) size group saury as the recruitment of winter- (spring-) cohort spawning in the Kuroshio region (the TZ) during autumn to winter (winter to spring). This is supported by the observations on larvae and juvenile and is consistent with the hypothesis that the medium and large size group saury are 0+ and 1+ year-class respectively (Kosaka, 2000). The latest study using otolith growth increments has also revealed that large and medium size groups of saury are different cohorts, and are corresponding to the winter- and spring-spawned cohorts, respectively (Kurita, Tohoku National Fisheries Research Institute of Japan, personal communication). Hence to understand the mechanism of the population dynamics of Pacific saury, it is important to identify the linkage between the abundance of saury and climate-oceanic system for the two spawned cohorts.

For the large size group saury, significant correlations between the abundance index and SST in the Kuroshio region, and SOI, and Sub High suggested that large size group saury are largely affected by climate and oceanic conditions from the equatorial to the subtropics. On the other hand, correlations between the abundance index of medium size group saury and SST in the TZ and the Oyashio region, and R2-ZI, and Sub High showed that the subarctic environments have a larger influence.

Cross-correlations between SSTs by waters and climate indices indicated that oceanic conditions in the northwestern Pacific are linked with the large-scale atmospheric circulation from the equatorial to high-latitude areas over the North Pacific (Table 2). Winter SST in the Kuroshio region is significantly correlated with SOI with a lag of 1 year (SOI leading SST), and with the winter Sub High, and with the winter R2-ZI, respectively. Significant correlations were also found between SOI and winter Sub High, and between winter Sub High and winter R2-ZI, indicating that the winter SST in the Kuroshio region are strongly associated with atmospheric circulations from the equatorial Pacific to the mid-latitude region. On the other hand, SST in the TZ and the Oyashio regions were significantly correlated with R2-ZI and Sub High, indicating that SST in the subarctic front zone is linked with atmospheric circulation from the subtropics to the subarctic region.

From the above relationships between SST and climates indices, we illustrated schematically the possible process of climate changes affecting the variability of saury abundance (Fig. 11). The variability

Table 2
Cross-correlation coefficients between SST and the climate indices during 1950–2000[a]

	SOI	Sub High	R2-ZI	R2-PV
SST-KR (winter)	−0.45**	+0.63**	+0.55**	n.s.[b]
SST-TZ (spring)	n.s.	−0.38**	+0.33*	n.s.
SST-OR (summer)	n.s.	−0.38**	−0.37**	n.s.
SOI	–	−0.43**	n.s.	n.s.
Sub High (winter)		–	+0.61**	n.s.
R2-ZI (winter)			–	n.s.
R2-PV (winter)				–

[a] SST-KR, SST-TZ and SST-OR represent SSTs in the Kuroshio, Kuroshio–Oyashio TZ and Oyashio regions, respectively.
[b] Not significant.
* Significant at the 5% level.
** Significant at the 1% level.

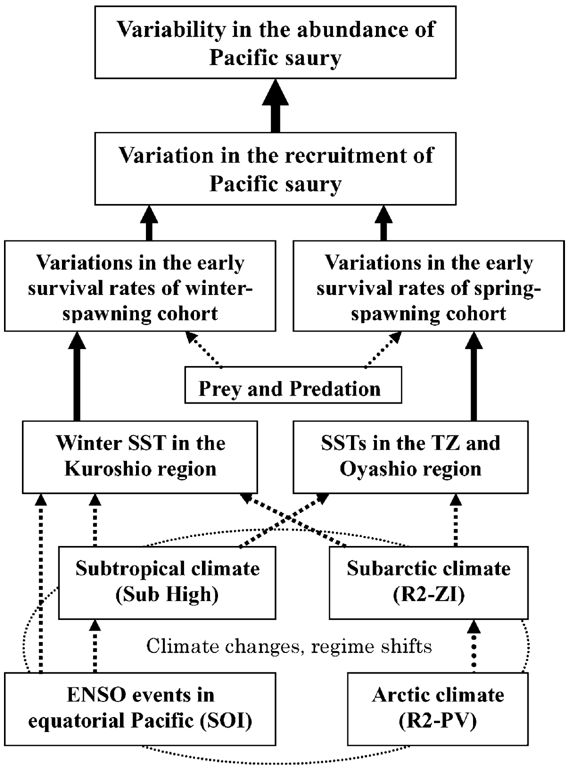

Fig. 11. Schematic diagram to show the possible process of oceanic-climate changes affecting the variability of Pacific saury. SST—sea surface temperature, TZ—Kuroshio–Oyashio TZ, SOI—southern oscillation index, Sub High—subtropical high pressure index, R2-ZI—far east zonal index, R2-PV—far east polar vortex index.

in the abundance of saury is determined by the recruitment of the large and medium size groups. The two size groups, which correspond to winter- and spring-spawned cohorts, respectively, have different life history with different spawning grounds and seasons. Survival rates in the early life stage for the two spawning cohorts are largely affected by SSTs in the Kuroshio region and the TZ, respectively. Differences in the early survival rates leaded to the difference in the recruitments for the two size groups, and resulted in the large variations in the abundance of saury. And regarding the environments, for the winter-spawned cohorts, there is no doubt that winter SST in Kuroshio region is a direct factor, and climate changes from equatorial Pacific to subtropics such as ENSO and westerly have potential impacts through atmosphere–ocean interactions, whereas spring-spawned cohorts were mainly affected by the SST in the subarctic front zone through atmosphere–ocean interactions from the subtropics to the subarctic region.

4.2. Effects of ENSO and climatic regime shifts

We demonstrated that ENSO events have significant impacts on the abundance of large size group saury (Figs. 8 and 9), and limited effects on medium size group saury. This is an important finding in understanding the mechanism of the population dynamics and in predicting the trend in the abundance. ENSO has a cycle of 2–5 years (Hanawa, 1989), large interannual variations in the abundance of large size group saury seemed to be responding to the ENSO cycles, and strong ENSO events have large impacts on the trend of saury abundance. It is well documented that ENSO events have large effects on the climate changes over the North Pacific, the SST fields in winter show positive (negative) anomalies over the wide zonal band along 30°N in the western North Pacific during the El Niño (La Niña) episodes (Hanawa, 1989). These are supported by our results that winter SSTs in the Kuroshio region are inversely correlated with SOI (Table 2). It is easy to understand that high correlation between SOI and abundance index of large size group saury is resulting from the effects of ENSO on SST fields in the subtropical northwestern Pacific.

Tsai et al. (1997) showed a linkage between recruitment of larval anchovy in coastal waters off south-western Taiwan and ENSO events through oceanographic and meteorological conditions and suggested that the Kuroshio current is an important mechanism of ENSO's teleconnections. Effects of ENSO on anchovy and mackerel in Korean waters seemed the same as the process of ENSO on the saury through SST fields (Kim and Kang, 2000). Limited effects of ENSO on the spring-cohort spawning in the TZ indicated that impacts of ENSO are limited to subtropical frontal zone (Nakamura et al., 1997). The subtropical front seems to be the boundary of oceanic-climate systems affecting the large (winter-spawned cohort) and medium (spring-spawned cohort) size group saury.

Besides the ENSO-like interannual variations in the abundance of the saury, there are also synchronous decadal variations with SST, strongly indicating the impact of long-term oceanic-climate changes in the North Pacific (Trenberth, 1990; Nakamura et al., 1997; Minobe and Mantua, 1999; Watanabe and Nitta, 1999). Variations in the abundance of pelagic fishes such as the sardine and salmon are largely associated with decadal climate changes (Mantua et al., 1997; Beamish et al., 1999; Yasuda et al., 1999). Historical records of saury catch also showed decadal-scale variations with abundant periods around the early 1910s, mid-1920s and early 1940s during the first half of last century (Fukushima, 1979). Decadal-scale variation patterns indicate that the abundance of saury response to long-term climate change beyond ENSO in the North Pacific.

A regime shift in atmospheric and oceanic conditions in the North Pacific occurred in 1976/1977, 1989/1990 and possibly around 1998 (Beamish et al., 1999; Watanabe and Nitta, 1999; McFarlane et al., 2000). Clear shifts in the abundance of saury occurred around 1963/1964, 1976/1977, 1987/1988 and 1997/1998 (Fig. 3), indicating the responses of saury to climatic regime shifts. This pattern is generally consistent with the regimes of British Columbia fisheries (Beamish et al., 2000). We can identify distinct shifts around 1986/1987 in the SSTs, and three ACIs, and changes in the above time series and SOI around 1997/1998 (Figs. 4 and 7). Zhang et al. (2000) pointed out that the 1976 and 1988 regime shifts closely associated with fluctuations in pelagic fisheries resource such as saury and the collapse of sardine in the northwestern Pacific. As the variation patterns of SSTs in the Kuroshio region and TZ are largely different, regional oceanic-climate indices representing the habitat environment such as winter SSTs in the Kuroshio region are useful in predicting the long-term trend in the abundance of Pacific saury.

4.3. Biological effects

Major food items of saury are copepods (Odate, 1977). Saury are preyed on by a number of large piscivious fishes such as pomfret, albacore and sharks, and the food web for Pacific saury is very complex (Brodeur, 1988). It is difficult to estimate quantitatively the biological effects such as prey–predator relationships have on the abundance of saury. Odate (1994) pointed out that the zooplankton biomass is not affected by the abundance of saury, although long-term variation in the catch of Pacific saury generally coincides with that for the zooplankton biomass in the Oyashio region. Growth and mortality rates of saury larvae were found to be stable for the winter-spawned cohorts in the Kuroshio region, whereas variable rates were found for the autumn- and spring-spawned cohorts in the TZ (Watanabe et al., 1997), although the zooplankton biomass in the TZ was higher than that in the Kuroshio region (Odate, 1994). This demonstrates that other factors than the zooplankton biomass are more important in the determination of the level of recruitment.

Laboratory experiments demonstrated that saury larvae have high survival rates and showed positive growth between 14 and 22 °C (Oozeki and Watanabe, 2000). The average temperature is 19.1 °C (with variance of 15.6%) in the Kuroshio region in winter, and is 15.9 °C (with variance of 30.2%) in the TZ in spring over the past 51 years. A high and stable spawning temperature is considered to result in the high growth and survival rates of winter-spawned cohorts in the Kuroshio region. Although biological effects such as prey–predation have some influence on the abundance of Pacific saury together with fishing effort, it seems that physical environments such as SST, which is linked to large-scale atmosphere–ocean systems from the equatorial to the high latitude area over the North Pacific, play a more important role in the determination of the year-class strength of Pacific saury for each spawned cohort.

5. Conclusions

We demonstrated that there is a linkage between the abundance of Pacific saury and oceanic-climate changes. Interannual and decadal variations in the abundance of Pacific saury seem to correspond with ENSO and decadal climate regime shifts, respectively. The abundances of Pacific saury were directly affected by SST fields through large-scale atmosphere–ocean interactions from the equatorial Pacific to mid- and high-latitude areas such as El Niño events.

ENSO events have marked impacts on the large size group saury. El Niño (La Niña) events have positive (negative) effects on the large size group saury with a lag of 1 year (ENSO leading saury). This is an important finding in understanding the mechanism of the population dynamics and in predicting the trend in the abundance for Pacific saury.

The large size group of saury was significantly correlated with the winter SST in the Kuroshio region, whereas the medium size group saury showed high correlations with the SST in the Kuroshio–Oyashio TZ and the Oyashio region, suggesting that the two size groups are affected by subtropical and subarctic oceanic environment, respectively.

Abundances of both the large and medium size group saury exhibit interannual–decadal variation patterns. But different variation patterns in the abundance of Pacific saury by size group and their different responses to oceanic-climate systems suggested that the large (medium) size group saury corresponds to the recruitments of winter- (spring-) cohort spawning in the Kuroshio region (the TZ). This is important in understanding the population structure of Pacific saury.

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References

Beamish, R.J., Noakes, D.J., McFarlane, G.A., Klyashtorin, L., Ivanov, V.V., Kurashov, V., 1999. The regime concept and natural trends in the production of Pacific salmon. Can. J. Fish. Aquat. Sci. 56, 516–526.

Beamish, R.J., McFarlane, G.A., King, J.R., 2000. Fisheries climatology: understanding decadal scale processes that naturally regulate British Columbia fish populations. In: Harrison, P.J., Parsons, T.R. (Eds.), Fisheries Oceanography: An Integrative Approach to Fisheries Ecology and Management. Blackwell Scientific Publishers, London, pp. 94–139.

Brodeur, R.D., 1988. Zoogeography and trophic ecology of the dominant epipelagic fishes in the northern North Pacific. Bull. Ocean. Res. Inst. Univ. Tokyo 26, 1–27.

Ebisawa, Y., Sunou, H., 1999. Influence of variation of the Kuroshio water on catch fluctuations of saury, *Cololabis saira*, in the waters off northeastern Japan. Bull. Ibaraki Pref. Fish Exp. Stn. 37, 29–36 (in Japanese).

Fukushima, S., 1979. Synoptic analysis of migration and fishing conditions of saury in the northwestern Pacific Ocean. Bull. Tohoku. Reg. Fish. Res. Lab. 41, 1–70 (in Japanese with English abstract).

Hanawa, K., 1989. Long-term variations in the physical environments in the Pacific Ocean. In: Kawasaki, T., Tanaka, S., Toba, Y., Taniguchi, A. (Eds.), Long-term Variability of Pelagic Fish Populations and Their Environment. Pergamon Press, London, pp. 19–28.

Kim, S., Kang, S., 2000. Ecological variations and El Niño effects off the southern coast of the Korean Peninsula during the last three decades. Fish. Oceanogr. 9, 239–247.

Kosaka, S., 2000. Life history of Pacific saury *Cololabis saira* in the Northwest Pacific and consideration of resource fluctuation based on it. Bull. Tohoku. Natl. Fish. Res. Inst. 63, 1–96 (in Japanese with English abstract).

Kurita, Y., 2001. Seasonal changes in spawning grounds and the abundance of egg-laying of Pacific saury. In: Annual Report of the Research Meeting on Saury Resource No. 49. Tohoku National Fisheries Research Institute, Aomori, pp. 203–205 (in Japanese).

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., Francis, R.C., 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bull. Am. Meteor. Soc. 78, 1069–1079.

Matsumiya, Y., Tanaka, S., 1974. Considerations on the so-called large- and intermediated-sized fish of saury on the basis of the analysis of the length composition. Bull. Tohoku. Reg. Fish. Res. Lab. 33, 1–18 (in Japanese with English abstract).

Matsumiya, Y., Tanaka, S., 1976. Dynamics of the saury population in the Pacific Ocean off northern Japan. I. Abundance index in number by size category and fishing ground. Bull. Jpn. Soc. Sci. Fish. 42, 277–286.

Matsumiya, Y., Tanaka, S., 1978. Dynamics of the saury population in the Pacific Ocean off northern Japan. III. Reproductive relations of large and medium sized fish. Bull. Jpn. Soc. Sci. Fish. 44, 451–455.

McFarlane, G.A., King, J.R., Beamish, R.J., 2000. Have there been recent changes in climate? Ask the fish. Prog. Oceanogr. 47, 147–169.

Minobe, S., Mantua, N., 1999. Interdecadal modulation of interannual atmospheric and oceanic variability over the North Pacific. Prog. Oceanogr. 43, 163–192.

Nakamura, H., Lin, G., Yamagawa, T., 1997. Decadal climate variability in the North Pacific during the recent decades. Bull. Am. Meteor. Soc. 78, 2215–2225.

Odate, K., 1977. On the feeding habits of the Pacific saury, *Cololabis saira* (Brevoort). Bull. Tohoku. Reg. Fish. Res. Lab. 38, 75–88 (in Japanese with English abstract).

Odate, K., 1994. Zooplankton biomass and its long-term variation in the western North Pacific Ocean, Tohoku sea area, Japan. Bull. Tohoku. Natl. Fish. Res. Inst. 56, 115–163 (in Japanese with English abstract).

Oozeki, Y., Watanabe, Y., 2000. Comparison of somatic growth and otolith increment growth in laboratory-reared larvae of Pacific saury, *Cololabis saira*, under different temperature conditions. Mar. Biol. 236, 349–359.

Oozeki, Y., Kitagawa, D., Kawai, T., 1998. Assessment method of the stock size of immigrated Pacific saury (*Cololabis saira*) including the information on the distribution outside the fishing grounds. Bull. Natl. Res. Inst. Fish. Sci. 12, 53–70 (in Japanese with English abstract).

Sinclair, M., Tremblay, M.J., 1985. El Niño events and variability in a Pacific mackerel (*Scomber japonicus*) survival index: support for Hjort's second hypothesis. Can. J. Fish. Aquat. Sci. 42, 602–608.

Sugimoto, T., Tadokoro, K., 1998. Interdecadal variations of plankton biomass and physical environment in the North Pacific. Fish. Oceanogr. 7, 289–299.

Tian, Y., Akamine, T., Suda, M., 2002. Long-term variability in the abundance of Pacific saury in the northwestern Pacific ocean and climate changes during the last century. Bull. Jpn. Soc. Fish. Oceanogr. 66, 16–25 (in Japanese with English abstract).

Tomosada, A., 1993. The relation of water temperature variation of the Tohoku sea area and circulation indices of atmosphere. Umi to Sora 69, 81–94 (in Japanese with English abstract).

Tomosada, A., Odate, K., 1995. Long-term variability in zooplankton biomass and environment. Umi to Sora 71, 1–7 (in Japanese with English abstract).

Trenberth, K.E., 1990. Recent observed interdecadal climate changes in the northern hemisphere. Bull. Am. Meteor. Soc. 71, 988–993.

Trenberth, K.E., Hurrell, J.W., 1995. Decadal coupled atmosphere–ocean variations in the North Pacific Ocean. In: Beamish, R.J. (Ed.), Climate Changes and Northern Fish Populations. Can. Spec. Pub. Fish. Aquat. Sci. No. 121, pp. 15–24.

Tsai, C.F., Chen, P.Y., Chen, C.P., Lee, M.A., Shian, G.Y., Lee, K.T., 1997. Fluctuation in abundance of larval anchovy and environmental conditions in coastal waters off south-western Taiwan as associated with the El Niño-southern oscillation. Fish. Oceanogr. 6, 238–249.

Watanabe, M., Nitta, T., 1999. Decadal changes in the atmospheric circulation and associated surface climate variations in the northern hemisphere. J. Climate. 12, 494–510.

Watanabe, Y., Butler, J.L., Mori, T., 1988. Growth of Pacific saury, *Cololabis saira*, in the northeastern and northwestern Pacific Ocean. Fish. Bull. US 86, 489–498.

Watanabe, Y., Oozeki, Y., Kitagawa, D., 1997. Larval parameters determining preschooling juvenile production of Pacific saury (*Cololabis saira*) in the northwestern Pacific. Can. J. Fish. Aquat. Sci. 54, 1067–1076.

Yasuda, I., Watanabe, Y., 1994. On the relationship between the Oyashio front and saury fishing grounds in the north-western Pacific: a forecasting method for fishing ground locations. Fish. Oceanogr. 3, 172–181.

Yasuda, I., Sugisaki, H., Watanabe, Y., Minobe, S., Oozeki, Y., 1999. Interdecadal variations in Japanese sardine and ocean/climate. Fish. Oceanogr. 8, 18–24.

Zhang, C.I., Lee, J.B., Kim, S., Oh, J.H., 2000. Climatic regime shifts and their impacts on marine ecosystems and fisheries resources in Korean waters. Prog. Oceanogr. 47, 171–190.