Climate-ocean variability and the response of Pacific saury (*Cololabis saira*) in the northwestern Pacific during the last half century

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SUMMARY: Effects of oceanic-climate changes on the abundance of Pacific saury (*Cololabis saira*) in the northwestern Pacific during the last half century were investigated. The abundance of both large and medium size groups of saury exhibits decadal-scale variation pattern, suggesting strong effects of decadal-scale changes or regime shifts in the oceanic environment. The abundance index of large size group saury is significantly correlated with the winter sea surface temperature (SST) in the Kuroshio region, the main spawning grounds in winter. The spatial and temporal response of large size group saury to SSTs demonstrated that winter SSTs in the Kuroshio region have marked impacts on the year-class success of the winter-spawning cohorts. The large size group saury also showed significant correlations with the Southern Oscillation Index (SOI) and Asian Monsoon Index (MOI), indicating effects of the El Niño Southern Oscillation (ENSO) and winter Asian Monsoon. Linkages between SST and SOI, and between SST and MOI demonstrated that the abundance of large size group saury were directly affected by the SST fields of the spawning grounds in the Kuroshio region in winter through large-scale atmosphere-ocean interactions such as ENSO events and the winter Asian monsoon.

KEY WORDS: **Pacific saury, abundance, decadal variation, SST, ENSO, MOI, climate change**

INTRODUCTION

Pacific saury (*Cololabis saira*) is one of the most important pelagic fishes in the northwestern Pacific. Pacific saury exhibits large interannual variations both in abundance and size composition. [1] Annual catches of saury in Japan have greatly fluctuated from 572,000 t in 1958 to 63,000 t in 1969 with an annual average of about 257,800 t from 1950 to 2000. Despite a decreasing trend in fishing efforts in the 1990's, the total catch of saury in 1998 dropped to 141,000 t which is less than half of that for the previous year, indicating a strong influence of environmental factors on the abundance of Pacific saury.

Pacific saury makes extensive migrations from the subtropical to the subarctic region throughout the Kuroshio-Oyashio Transition Zone (TZ) where complex oceanic structures occur (Fig. 1). 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. The spawning season of Pacific saury continues from autumn through spring, shifting spawning grounds from the TZ to the Kuroshio region. [2] Larval growth and survival rates of the saury largely vary with spawning cohorts. Winter-cohort spawning in the Kuroshio region and spring-cohort spawning in the TZ have high survival rates compared with autumn-cohort spawning in the TZ, [2] suggesting that winter- and spring-cohorts play an important role in the determination of the recruitment.

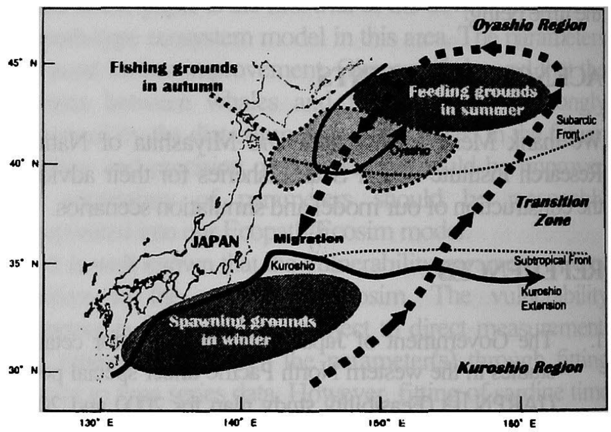

Fig. 1 Life history and migration pattern of Pacific saury with oceanographic features.

Formations of saury fishing grounds largely depend on the oceanographic conditions. [3] However, impacts of the oceanographic conditions on the population dynamics of the saury are poorly understood. Matsumiya and Tanaka [4] pointed out that the abundance of saury is seriously affected by its reproductive success or failure, and the drastic population decline does not directly result from overfishing. 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. [5] Recent studies have also revealed that the North Pacific atmosphere-ocean system fluctuates with a decadal scale. [6] The purpose of this study is to unravel the mechanisms whereby the variability in climate and oceanic conditions are linked to the population dynamics of Pacific saury.

DATA AND METHODS

Saury catch in number of fish with the size composition from 1951 to 2000 was provided from Tohoku National Fisheries Research Institute of Japan. Length frequency analysis (LFA) [7] showed that the saury are distinguished as two groups, the large and the medium size groups, for most years during the past 50 years, indicating that the population of Pacific saury is dominated by the two groups. Accordingly, here we use the catch in number of fish by size group estimated from LFA 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 assumed to correspond to different spawning cohorts.

A sea surface temperature (SST) data set for the northwestern Pacific was provided from the Japan Meteorological Agency (JMA). This data set has 1° grid (longitude×latitude) resolution. SSTs for each grid were correlated with the abundance index of saury. Here, we also use three area-averaged time series of monthly mean SST extracted from the JMA data set to relate to the abundance index of saury. The three time series of SST are 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), which approximately represent the subtropical frontal zone (STFZ), the TZ and subarctic frontal zone (SAFZ), respectively.

Southern Oscillation Index (SOI) and Monsoon Index (MOI) were used as climate indices to investigate the effects of large-scale atmospheric-oceanic interactions on the saury. SOI is defined as the difference in the sea level pressures between Darwin (Australia) and Tahiti. It is an index of El Niño Southern Oscillation (ENSO), with extreme negative (positive) values of SOI represent El Niño (La Niña) episodes. MOI is the difference in the sea level pressure between Irkutsk (Russia) and Nemuro (Japan), is an index of winter Asian monsoon. Both ENSO and Asian monsoon in winter have marked impacts on the climate and waters of Japan.

RESULTS

Both the large and medium size group saury have shown large interannual variations in their abundances during the past 50 years (Fig. 2). The abundance index of large size group saury increased during the period from 1954 to 1962, decreased sharply from 1963 to 1977 (a great recovery in 1973), sustained a relatively stable period from 1978 to 1987, and increased rapidly during 1988 to 1997. Abrupt changes occurred around 1953/54, 1962/63, 1977/78, 1987/88 and 1997/98. This pattern strongly indicates decadal-scale variations together with large interannual fluctuations in the abundance. Despite a descending trend in fishing efforts in the 1990's, the abundance index of large size group saury experienced an abrupt decline in 1998 from an abundant period, indicating the strong influence of environmental factors on the trend of the abundance.

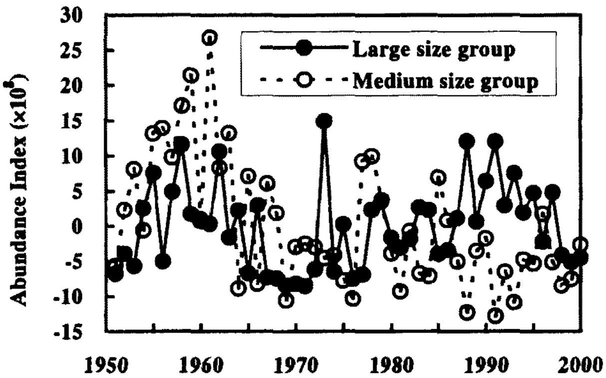

Fig. 2 Annual anomalies (differences from the average during 1951 to 2000) of abundance index for large (solid circles) and medium (open circles) size group saury during 1951 to 2000.

The variation patterns for the medium size group saury are almost similar to those of large size saury until 1976. After 1977, however, particularly after 1987, the patterns are completely opposite to the large size group saury, indicating variations in the abundance for the two groups are different and may respond to the different oceanic systems.

SSTs showed large differences between oceanic regions. Averages of annual mean SST during the past 51 years are 23.0°C (C.V. 7.0%) in the Kuroshio region, 17.8°C (C.V. 23.7%) in the TZ and 9.9°C (C.V. 21.0%) in the Oyashio region, respectively. SSTs for all of the three areas showed clear decadal scale variation patterns. There has been a long descending trend with large annual variations for annual mean SSTs in the TZ and Oyashio regions from 1950 to 1986, while an ascending pattern is clear in the Kuroshio region after the 1970's. Variation patterns in the SSTs for the Oyashio region and TZ are similar, but are different with that in the Kuroshio region, indicating that two different oceanic systems occur affecting the Kuroshio and the Oyashio regions.

The abundance index of large size group saury is significantly correlated with the SSTs in the Kuroshio region during Jan. to Apr. over the past 50 years (Fig. 3). In particular, the large size group saury showed a good correspondence with winter (Jan. to Mar.) SSTs in the Kuroshio region on both interannual and decadal scales, with the correlation between the winter SST in the Kuroshio region and the abundance index of large size saury being significant at the 99% level (r=0.47, p<0.01).

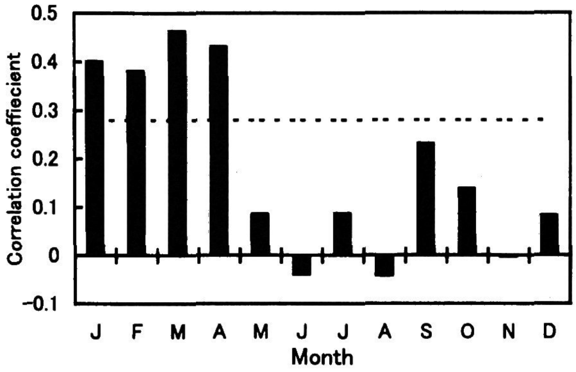

Fig. 3 Correlation coefficients between the abundance index of large size group saury and the monthly SST in the Kuroshio region during 1951 to 2000. The dashed line indicates the 95% significance level.

Spatial distribution patterns of correlation coefficients between the large size group saury and SSTs showed that the areas of high correlations expanded from the inshore to the offshore along the Kuroshio Current and Kuroshio Extension during January to April (Fig. 4). The SSTs showing high correlations with the saury centered in the area of Kuroshio Current and Kuroshio Extension, indicating the oceanic environments in STFZ have a strong influence on the large size group saury, whereas the impacts of the subarctic climate on the large size group saury is limited. There is no significant relationship between the large size group saury and SSTs in SAFZ.

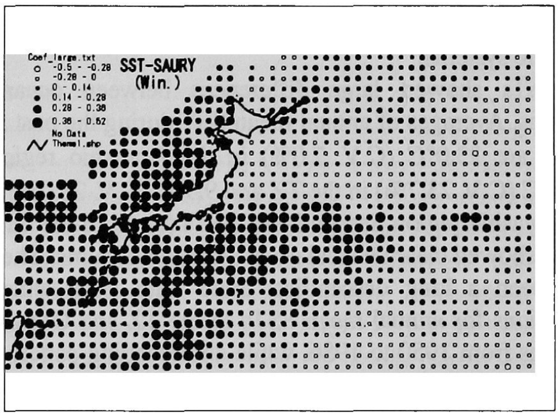

Fig. 4 Correlation coefficients between the abundance index of large size group saury and the SSTs in winter during 1951 to 2000. Note correlations for the data in the East China Sea and Japan Sea should be disregarded because these areas are out of the distribution for saury.

On the other hand, the medium size group saury showed a high correlation with the SSTs in the TZ and Oyashio region during July and early autumn, indicating that the SAFZ has larger influence than the STFZ.

Cross correlation between SOI and saury showed that the large size group correlated significantly with SOI with a time lag of one year (SOI leading saury), suggesting that El Niño (La Niña) have positive (negative) effects on large size saury (Fig. 5-A). It is worth noting that the abundant period for large size group saury in 1990's corresponds closely with the long and strong El Niño trends, and the low abundance level during mid-1960's to mid-1970's is closely associated with the frequent La Niña events. Interanual variations in the abundance of the large size group saury seems to correspond to the ENSO.

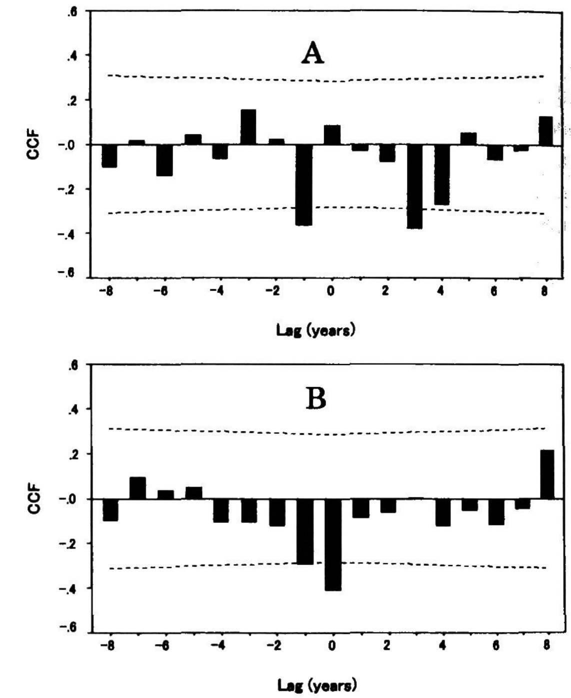

Fig. 5 (A) Cross correlation functions (CCF) between the Southern Oscillation Index (SOI) and the abundance index of large size group saury. (B) Cross correlation functions (CCF) between the winter monsoon index (MOI) and the abundance index of large size group saury. The dashed lines indicate the 95% significance level.

Winter MOI in the following and previous years showed significant negative correlations with the large size group saury, indicating that the intensity (weakness) of Asian monsoon in winter (north wind) has negative (positive) effects on large size group saury (Fig. 5-B). The high abundance of large size group saury after 1987 corresponds closely with the weakened trend in MOI.

On the other hand, no significant correlations were found between the medium size group saury and SOI, and MOI, indicating that effects of ENSO events and Asian Monsoon are limited and the mechanisms affecting the medium size saury are different to the large size group saury.

DISCUSSION

Interannual-decadal variations in the abundance of both large and medium size saury strongly suggest the effects of oceanic-climate changes. It seems that the interannual and decadal variations in the abundance of Pacific saury respond to ENSO and climatic regime shifts, respectively.

Synchronous patterns between the abundance index of saury and SST demonstrated that the large size group saury is directly forced by the SST fields of spawning grounds. Different patterns in the abundance for the two size groups and different responses to SST fields indicated that the large and the medium size group saury are different spawning cohorts, and are affected by two different oceanic systems.

Our results strongly suggest that the year-class success of the large size group saury is determined by SSTs in the Kuroshio region in winter. Distributions of larvae and juveniles of saury in winter from direct observations are consistent with the areas where the large size group saury correlated significantly with the SST, [8] suggesting the large size saury corresponds to winter cohorts spawned in the Kuroshio region. Resent surveys also confirmed that spawning of saury in the Kuroshio region continues from autumn through spring with a peak in winter. Because the autumn-cohort spawned in the TZ has a high mortality [2] and is assumed to migrate to the Kuroshio region to overwinter, it is reasonable to regard the large size group saury as recruits from cohorts spawning during autumn to winter (winter-cohort), considering the long spawning season and migration pattern of the saury. Accordingly, the medium size group saury corresponds to the cohorts spawning during winter and spring (spring-cohorts). This is consistent with the hypothesis that the medium and the large size group saury are 0+ and 1+ year-class, respectively. [8] This is an important finding in understanding the structure and dynamics of saury population in the northwestern Pacific.

Significant correlations between the abundance index of the saury and SSTs, SOI, and MOI suggest that large size group saury is largely affected by oceanic conditions of STFZ in winter, and linked with large-scale climate changes such as ENSO and winter Asian monsoon. Cross correlations between the SSTs and climate indices demonstrated that the variability of SST field in STFZ is linked with ENSO and Asian monsoon. The previous El Niño (La Niña) events lead to positive (negative) SST anomalies in STFZ. [9] ENSO seems to affect the saury through SSTs in winter. Positive (negative) response to previous El Niño (La Niña) events for large size group saury suggests the possibility in prediction of the abundance trend for Pacific saury.

Good response of large size saury to MOI suggested the MOI is a useful index together with SOI. Winter Asian monsoon (north wind) has large impacts on the vertical mixing in the western Pacific. MOI in the following and previous years explained 64% variability in winter SSTs of the Kuroshio region. The warm trend in SSTs after 1987 in the northwestern Pacific, particularly in STFZ, is consistent with the weakness of MOI. It is easy to understand that the large size group saury is affected by the winter monsoon through SSTs of spawning grounds just as the ENSO's teleconnection on the saury.

There is no doubt that the abundance of the large size group saury is affected by the SST fields through large-scale atmosphere-ocean interactions from equatorial Pacific to mid-latitudes such as El Niño and Asian monsoon. The abundance of the medium size group saury is closely associated with subarctic environments, but the mechanism seems more complicated compared with the large size group saury. One reason may be the large variability in the TZ.

ACKNOWLEDGEMENTS

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