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Year-to-Year and Inter-Decadal Fluctuations in Abundance of Pelagic Fish Populations in Relation to Climate-Induced Oceanic Conditions

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ABSTRACT: Ocean climate variables (1900~2005), time series of catches (1910~2005) and body size data were used to assess the year-to-year and decadal scale fluctuations in abundance of the fish populations (Japanese sardine, anchovy, jack mackerel, chub mackerel, Pacific saury and common squid) that have spawning grounds in the East China Sea and its adjacent regions. A negative correlation between the abundance of pelagic fishes (e.g. jack mackerel) in the Tsushima Warm Current (TWC) region and the Kuroshio-Oyashio Current (KOC) region was attributed to the climatic modulation of larval transport and recruitment, which depends on the winter monsoon-induced drift, current systems, and spawning season and site. The changes in abundance and alternation of dominant fish populations in the two regions in the 1930s, 1970s, and late 1980s mirrored changes in the climate indices (ALPI, AOI and MOI). Oscillations in the decadal climate shifts between the two regions led to zonal differences in larval transport and recruitment, and hence differences in the abundance of the pelagic fish populations. During deep Aleutian Lows, as in the 1980s, larval transport from the East China Sea to the KOC region increases in association with the strong winter Asian monsoon, cool regime and increased volume transport of the Kuroshio Current systems, whereas during a weak Aleutian Low (as in the 1990s), larval transport to the TWC region increased in association with a weak winter Asian monsoon, a warm regime, and increased volume transport of the Tsushima current system. We postulate that the increased chub mackerel abundance in the TWC region and the decreased abundance in the KOC region in the 1990s are partly attributed to changes in recruitment and availability to the fishing fleets under the warm regime in the spawning and nursery grounds in the East China Sea in association with the quasi-steady state of mild winter monsoon in the 1990s. The fluctuations in chub mackerel and jack mackerel abundance are under the environment-dependant growth form, although the tropicalization was identified in the TWC region. The density-dependant growth form was found in Japanese sardine populations, but no tropicalization by fishing was identified in the long (10~15 year) periods of abundance despite their short (3~4 year) generation time, suggesting that the environment-dependant growth form drove the changes in abundance. Year-to-year and decadal scale variations in abundance and population structure of the Pacific saury responded to climate regime shifts (1976/1977, 1988/1989), suggesting that the fish is a key bio-indicators for changes in the ecosystem.

Key words: Abundance, Climate shifts, Density-dependant growth, Fish population, Juveniles, Kuroshio, Oceanic conditions, Recruitment, Transport, Tropicalization, Tsushima Warm Current

INTRODUCTION

There are several hypotheses about the impact of large-scale climate changes beginning in the late 1970s on marine ecosystems in the North Pacific (Trenberth and Hurrell 1994, Polovina et al. 1995, Yatsu et al. 2005). Some pelagic fish species show large variance in their distribution ranges due to alternating expansions and contractions. The abundance of sardines increases in the western boundary current system when local waters are cool and more productive (e.g., in the 1980s), whereas it increases in the eastern boundary current systems when the regions are warm and less productive (Chavez et al. 2003, Bakun and Broad 2003). It has been observed that the abrupt changes in fish communities in the East/Japan Sea that occurred in the mid 1970s and late 1980s corresponded closely with climate regime shifts in the North Pacific (Tian et al. 2006).

Watabe (1992a, 1992b), Kawasaki (1993), Schwartzlose et al. (1999) and Klyashtorin (2001) all observed that dominant fish species alternate in the western and eastern boundary current systems. Research on catch trends in fish populations around the world suggests some degree of local rather than remote synchrony (Freon et

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al. 2003). For example, regional synchrony in the long-term fluctuations of fish populations and alternation of dominant species was identified in the TWC region (Ogawa and Nakahara 1979, Gong et al. 2007). Several important pelagic fish species (chub mackerel, jack mackerel, Japanese sardine, Japanese anchovy, Pacific saury, and common squid) have their spawning grounds in the East China Sea and its adjacent regions. However, their main spawning grounds and seasons do not completely overlap.

Regional differences in abundance of pelagic fishes between the TWC and KOC regions as measured by long-term catch trends are not always consistent across species. The regional differences in catch of jack mackerel (TWC > KOC) and Pacific saury (TWC < KOC) are attributed to their limited distribution and availability in the fisheries (Gong et al. 2007). The catch of jack mackerel in the TWC region was negatively correlated with that in the KOC region, which suggests that recruitment may oscillate between the two fisheries as a result of fluctuations in the rate of larval transport from the spawning grounds (Uehara and Mitani 2004, Morinaga 2004, Gong et al. 2007). Several factors, including ocean climate shifts, density-dependant reproduction, intra- and interspecific interactions, and fishing pressure seem to influence the abundance of pelagic fish populations. However, the major causes of short-term and long-term regional fluctuations in abundance of commercially important fish populations are not yet well-understood in the Far-Eastern region.

We examine the ways in which climate-induced oceanic changes have produced year-to-year and decadal changes in recruitment and abundance of the pelagic fish populations in two regions in the Far East.

MATERIALS AND METHODS

The ocean current systems in the northwestern Pacific and its adjacent regions have been examined in previous studies (e.g., Gong et al. 2007; Fig. 1). The thermal structure of the continental shelf zone during the winter monsoon was determined using satellite measurements of the winter time sea surface temperature (SST) in the East China and Yellow Seas (Fig. 2). Hypothetical migration circuits for 7 pelagic fish species were established based on the ocean current systems, spawning grounds, estimates of larval transport by the currents, and fishing data (Fig. 4).

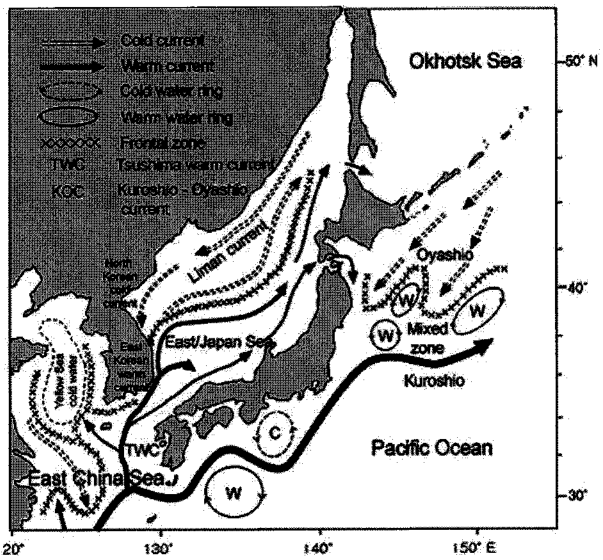


Fig. 1. Schematic of ocean current systems in Far-Eastern waters. The TWC(Tsushima Warm Current) region includes the Korea Strait, the East/Japan Sea, the East China Sea and the Yellow Sea, and the KOC (Kuroshio-Oyashio Current) region includes the northwestern Pacific including the Okhotsk Sea, Seto Inland, and the Tsugaru Strait (after Gong et al. 2007).

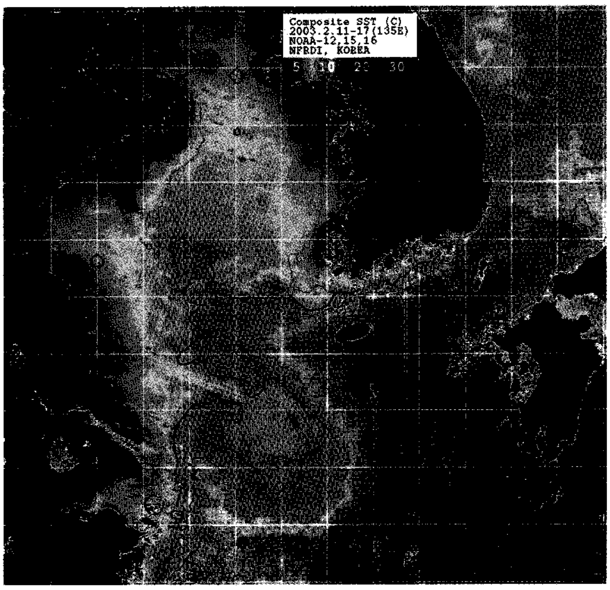


Fig. 2. Sea surface temperatures from 11～17 February 2003 in the East China Sea, the Korea Strait, and the Yellow Sea, from NOAA infrared imagery.

The Arctic Oscillation Index (AOI), Aleutian Low Pressure Index (ALPI) and Monsoon Index (MOI) were chosen as climate indices for the Far East region (Fig. 3). Several additional types of meteorological and oceanographic data, including geostrophic wind velocity (Fig. 7), volume transport of the Kuroshio in the southeastern East China Sea (Fig. 8), temperature anomalies and positions of frontal zones in Far-Eastern waters (Fig. 9), and the strength of the Tsushima Warm Current system (Fig. 10), were also used to assess the regional climate and ocean conditions in the East China Sea and adjacent regions.

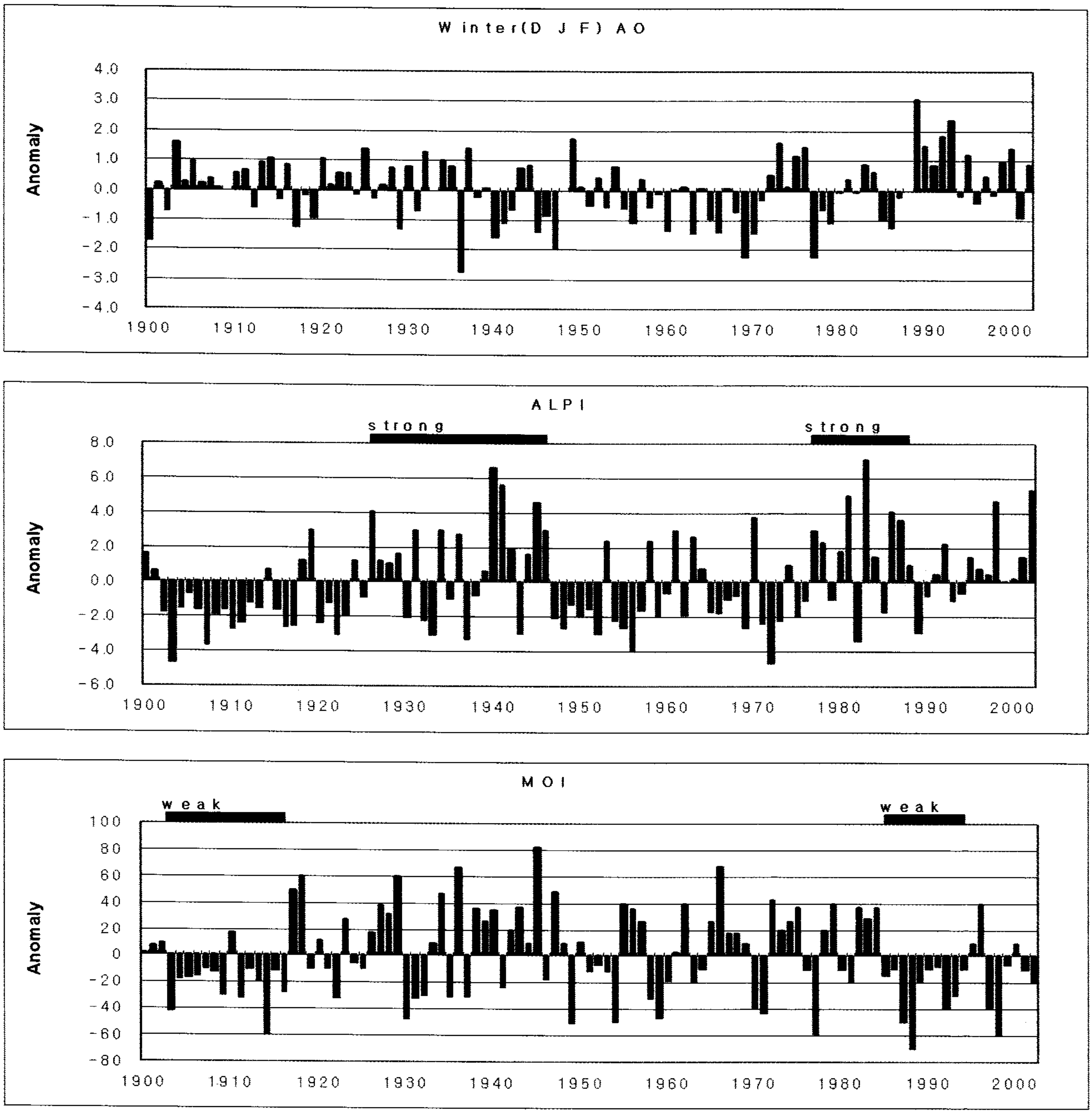
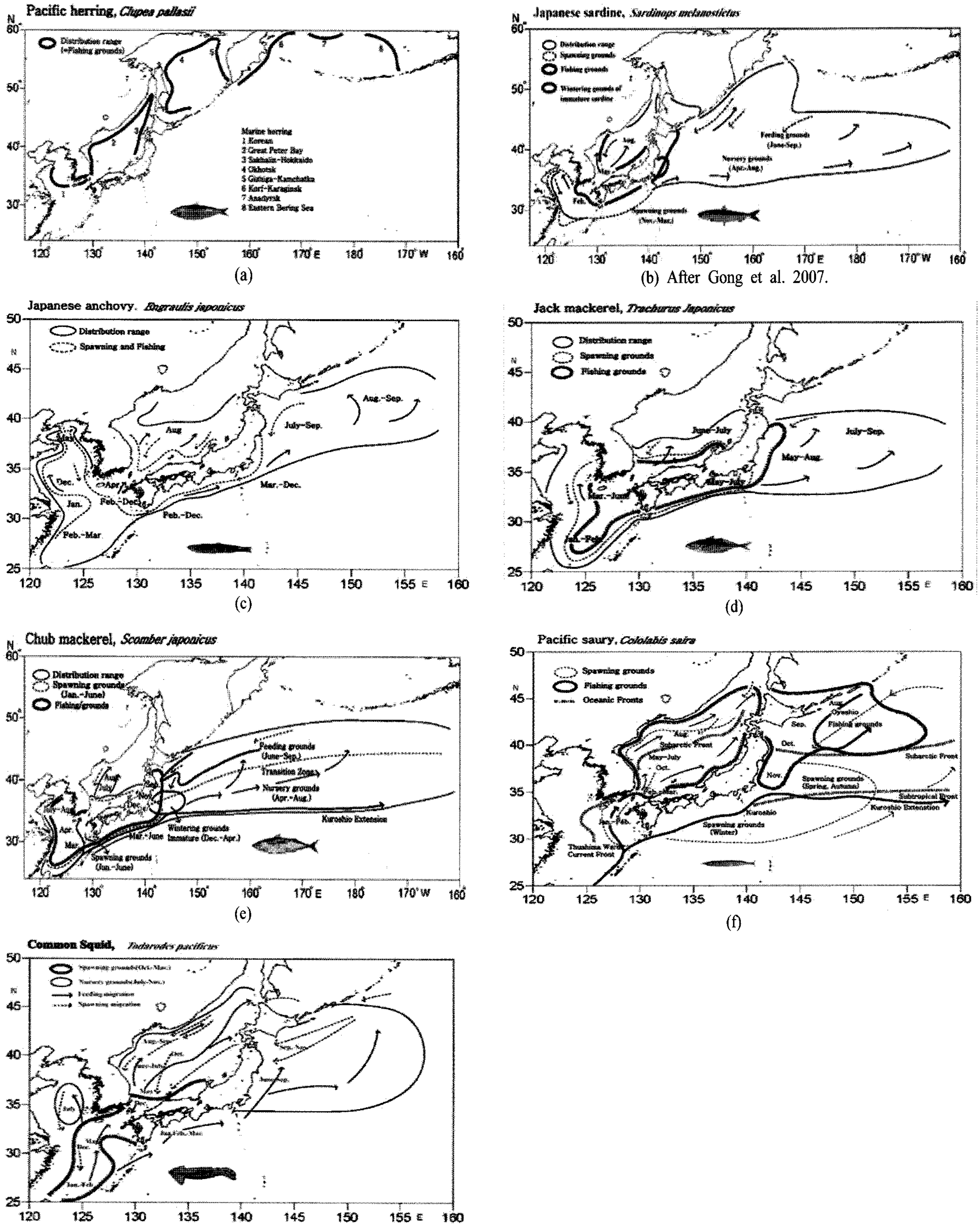


Fig. 3. The Arctic Oscillation Index (AO), Aleutian Low Pressure Index (ALPI), and Monsoon Index (MOI) from1900~2002. The strong ALPI in the 1930s and 1980s and weaker winter monsoon (MOI) in the 1900s and 1990s are marked by black bars.

Time series of catches for seven pelagic fishes (Pacific herring, Japanese sardine, anchovy, chub mackerel, jack mackerel, Pacific saury and common squid) that have spawning grounds in the East China Sea and its adjacent regions were constructed for the Tsushima Warm Current (TWC) region and the Kuroshio-Oyashio Current (KOC) region (Fig. 6). The TWC region covers the Yellow Sea, the East China Sea and the East/Japan Sea, and the KOC region covers the northwest Pacific including the Seto Inland Sea, the Tsugaru Strait, and the Okhotsk Sea. The catch rate for each pelagic fish species by the Korean fishing fleet displays remarkable monthly variation (Fig. 5), suggesting that fishing is conducted across only a small part of the population range. Therefore, fishing records from Japan, China/Taiwan, and Russia were also included in our regional catch data to examine the short-term and long-term trends in abundance of the fish populations (Fig. 6). The historical catch data for the period 1905~2005 are based on the Year-books of Fishery Statistics of China/Taiwan, Korea, Japan and Russia and previous reports including fishery data (Chikuni 1985, Schwartzlose



(a)

(b) After Gong et al. 2007.

(c)

(d)

(e)

(f)

(g) After Gong et al. 2007.

Fig. 4. Migration circuits of pelagic fishes with spawning grounds in the East China Sea and its adjacent regions; (a) Pacific herring, (b) Japanese sardines, (c) Japanese anchovies, (d) Jack mackerel, (e) Chub mackerel, (f) Pacific saury and (g) common squid.

et al. 1999, Klyashtorin 2001, Gong et al. 2007). The relationship between the catch and catch per unit fishing effort (CPUE) was also examined to see if the catch series can be considered to be indices of fluctuations in population abundance.

Life cycles, habitats, distribution, and the nature of fishing activities for seven pelagic fish species are presented to facilitate comparisons in their responses to changes in the ocean climate and fishing pressure (Table 1).

Table 1. Life cycle, habitat and distribution for the seven pelagic fish species which have spawning grounds in the East China Sea and its adjacent regions

Common name	Japanese anchovy	Jack mackerel	Chub mackerel	Japanese sardine
Scientific name	*Engraulis japonicus*	*Trachurus japonicus*	*Scomber japonicus*	*Sardinops melanostictus*
Life span (years)	4	6	7	7~8
Maximum body length (cm)	14	40	40	25
Age at maturity (years)	1	1 (low level) 2 (high level)	2 (low level) 3 (high level)	1 (low level) 3 (high level)
Spawning season /area	Mar.~June East China sea May~Oct, (Yellow Sea), NW Pacific	Dec.~July (mainly Feb~July) East China Sea, adjacent region	Jan.~July (mainly Mar.~July) East China Sea, NW Pacific, Korea Strait	Dec.~June (mainly Feb.~May) East China Sea, Northwest Pacific, Korea Strait and adjacent regions
Community level, corresponding to demersal comm. Groups	Okaba community-Ⅰ	Okaba community-Ⅱ	Okaba community-Ⅱ(young fish) Ⅲ(adult)	Okaba community-Ⅲ
Optimum habitat; salinity and temperature range	17~24 ℃ low haline/ warm water origin	15~22℃ high haline/ warm water origin	14~21℃ (young) mild temp. 12~16℃ (adult) cool temp.	13~15℃ cold water origin
Main food for adult fish	Zooplankton (copepod etc.)	Zooplankton (copepod etc.)	Zooplankton (copepod, Euphausia), anchovy, squid salps.	Phytoplankton (diatom), Zooplankton (copepod etc.)
Main food for larvae and juveniles	Corycaeus, Paracalanus, Oncea etc.	Corycaeus	Neocalanus, Eucalanus, Corycaeus	Paracalanus Corycaeus, Oncea etc.

Common name	Pacific herring	Pacific saury	Common squid
Scientific name	*Clupea pallasii*	*Cololabis saira*	*Todarodes pacificus*
Life span (years)	7~8 (5~15)	1~1.5	1
Maximum body Length	30 (52) cm	34	30 (DML)
Age at maturity (years)	2 (4~5), 2 cm	1 (20)	0.8 (20)
Spawning season/area	Feb~May/coastal zone, north of 35° N	Sep.~June /30~45°N, 125~160°E	Autumn~winter/ 25~40°N, 122~144° E
Community level, corresponding to demersal comm. group	Taraba community-1	Okaba community-11	Okaba community-11
Optimum habitat; temperature, salinity ranges	Pelagic-mesopelagic, 0~250 m, 0~7℃ (4~7℃)	Epipelagic, offshore, 0~100 m, 10~22℃ (12~19℃), 33.6~34.8 psu	Coastal-offshore, 0~250 m, 7~23℃ (12~18℃)
Main food for adult fish	Zooplankton	Zooplankton	Zooplankton
Main food for larvae, juveniles	Corycaeus	Corycaeus	Corycaeus

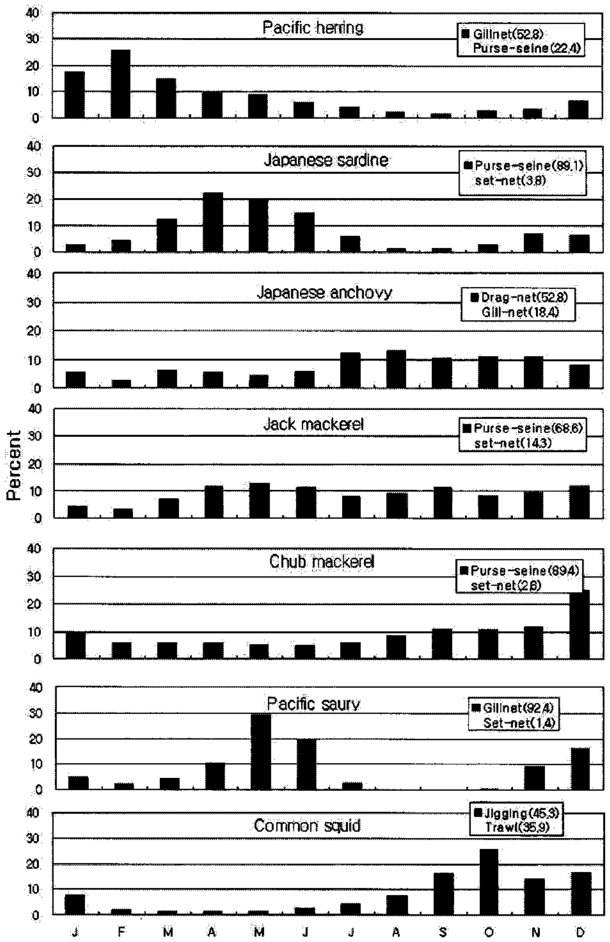


Fig. 5. Main fishing gears and monthly catch in percent of 7 pelagic fishes by Korean fishing in the waters off Korea (one part of TWC region), 1971~2004.

Mean body size (fork length) of the fishes for each year in the period 1960~2005 was used as a biological index representing the growth, nutritional state, and tropicalization in non-tropical waters resulting from fishing (Figs. 10 and 11). The time series of body sizes clearly show that heavy fishing in non-tropical waters "tropicalizes" fish stocks in the sense that it drives them to exhibit the characteristics of their tropical counterparts (i.e., smaller body size and earlier maturation: Pauly 1998, Stergiou 2002). The biological data, fishing grounds, and spawning grounds for the pelagic fishes are derived from previous reports (NFRDI 1985, 1994, 1998, 2005, Gong and Suh 2004, Sassa et al. 2006, Gong et al. 2007).

The relationships among ocean climate indices, abundance of the fishes, and body sizes were examined to distinguish between the effects of natural forcing (ocean climate forcing) and human activities (fishing) on fish stocks. The mechanisms promoting short-term changes and regional differences in the recruitment and abundance of the fishes associated with climate-induced oceanic conditions (e.g., thermal conditions and strength of the current systems) were then extended to explain the decadal scale changes in total and regional fish abundance in the Far East.

RESULTS

Zonal Oscillation in Climate-Induced Oceanic Conditions

In years with abnormally strong winter wind speeds (e.g. 1957/58, 1962/63, 1967/68), sea temperatures were far below normal in winter and spring in the East China Sea (Figs. 7 and 9). The Kuroshio Volume Transport (KVT) in the southern East China Sea increased in association with strong cyclonic circulation in the subarctic region and strong anticyclonic circulation in the subtropical region of the western Pacific with the deep Aleutian Low Pressure (ALP). The strength of the Tsushima Warm Current system decreased in association with strong winter monsoons (as measured by the MOI) and the deep ALP in the 1980s (Figs. 3, 8, 9, and 10).

The KVT decreased in association with weak cyclonic circulation and anticyclonic circulation in the Pacific with the weak ALP, while the strength of the Tsushima Warm Current increased and the thermal regime was above the long-term mean in the TWC region in association with the weak winter monsoon and the weak ALP in the 1990s (after the climate regime shifts, 1988/89).

Climate Shifts and Changes in Abundance of the Fish Populations in the TWC and KOC Region

Changes in abundance of several pelagic fish species (e.g., Japanese sardine, jack mackerel, anchovy, chub mackerel, Pacific saury, and common squid) were clearly associated with changes in the Arctic Oscillation Index (AOI), Aleutian Low Pressure Index (ALPI) and Monsoon Index (MOI) in the 1930s, the late 1960s and mid 1970s, and the end of 1980s (Figs. 3 and 6). Annual jack mackerel catch showed large fluctuations and ranged from 55,000 to 575,000 tons in the period 1926~2005 (Fig. 6d). Relationships among the winter monsoon, sea temperatures, positions of thermal fronts, and shifts in jack mackerel catch from the TWC to the KOC region were investigated for periods of abundance in the 1960s and 1990s. The catch of jack mackerel decreased in the TWC and increased in the KOC region in years with cool sea temperatures in association with the strong winter monsoon (e.g. 1963, 1968, 1986 and 1996), which suggests climatic modulation of larval transport between the TWC and KOC region. The total catch (TWC+KOC) of jack mackerel decreased in years when the catch shifted from the TWC to the KOC region (Figs. 6d, 7, 9), which suggests that production or susceptibility to fishing were disturbed by the strong winter monsoon.

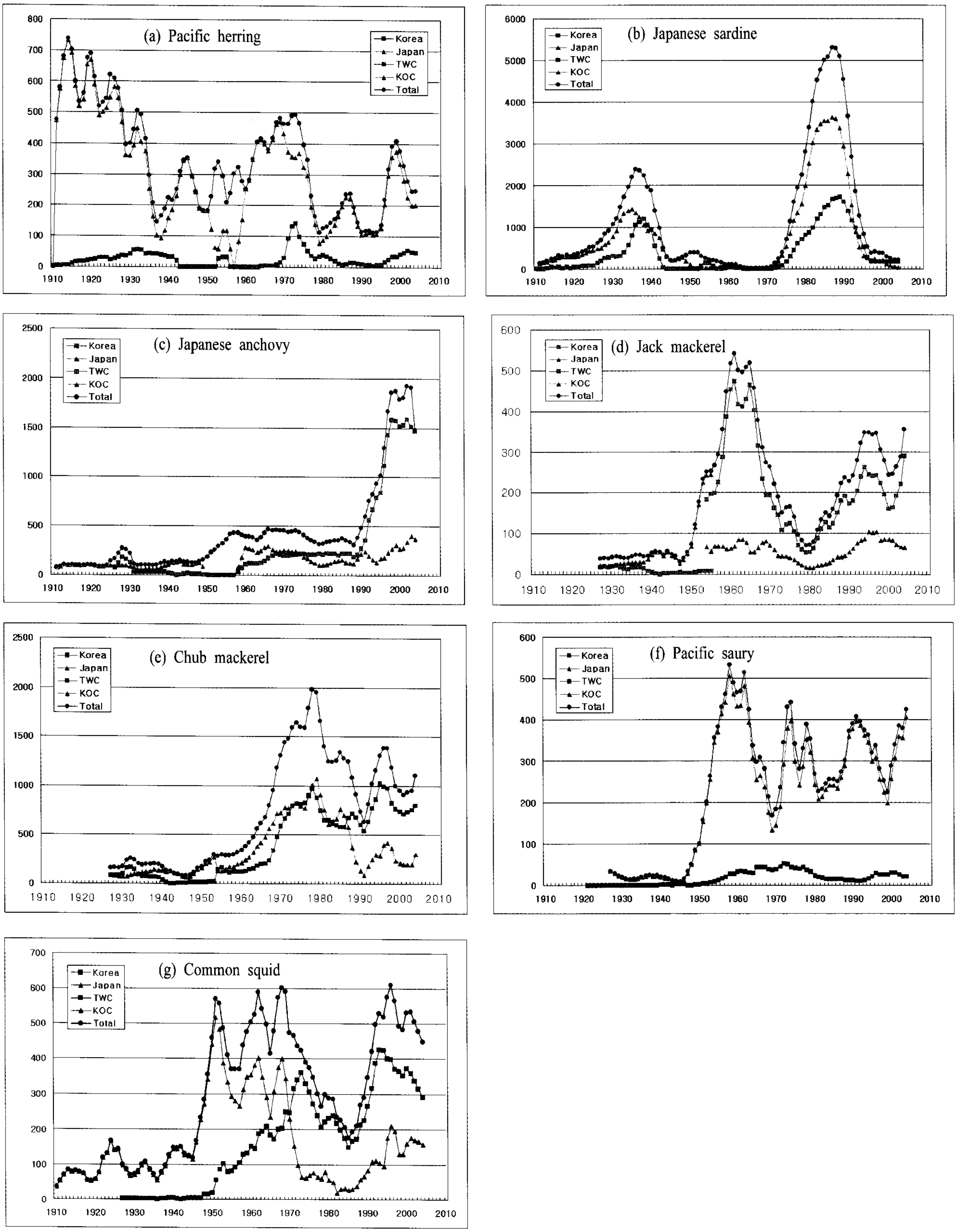


Fig. 6. Time series of catches(3 years running average) for pelage fishes in the TWC(Yellow Sea-East China Sea-East/Japan Sea) and KOC(Northwest Pacific-Okhotsk Sea) regions during 1910~2005. Unit in Y-axis is 1,000 tons.

Regional Differences in Recruitment by Wind-induced Transportation of Larvae

The recruitment of fish in fisheries can be affected by the rates of larval transportation to different regions resulting from spawning patterns, winter monsoon-induced wind-drifts, the strength of ocean current systems, and the density of eggs and larvae. The stronger the winter monsoon, the further southeastward the larvae and juveniles are transported by the Kuroshio from the East China Sea to the Pacific side (KOC region), and hence recruitment (and availability to the fishing fleets) in the KOC region will increase, while recruitment in the TWC region decreases (Table 2).

① Under typical ocean climatic conditions, an estimated 80 percent of the larvae and juveniles produced in the East China Sea in winter months were available to the fishing fleets in the TWC region, and the remainder were transported to the Pacific side (KOC region), where some of them were not available to fishing fleets due to their subsequent emigration from the fishing grounds, particularly in the Kuroshio region off eastern Japan.

② Under abnormally cool regimes associated with strong winter monsoons, about 70 percent of the larvae and juveniles are estimated to be available to fishing fleets in the TWC region and the reminder were transported to the Pacific side (KOC).

③ Under abnormally warm regimes associated with weak winter monsoons, most (~90 percent) larvae and juveniles remain in the East China Sea and migrate to areas in the north including the Korea Strait, the East/Japan Sea, and the Yellow Sea (TWC region). Only an estimated 10 percent are transported to the KOC region, where some are not available to fishing fleets due to subsequent emigration from the fishing grounds.

Inter-Decadal Fluctuations in Abundance of Fish Populations and Climate Changes

Comparisons of the long-term climate indices (AOI, ALPI and MOI; Fig. 3) and oceanic conditions (Figs. 8, 9, and 10) with the abundance (in terms of catch) of the pelagic fish species (Fig. 6) found that the fish were more abundant in the TWC region than in the KOC region during the mild and warm regimes associated with mild winter monsoons in the late 1950s, early 1960s, and the 1990s. During the cool regime between the climate shifts in the early 1970s and late 1980s, the jack mackerel and anchovy populations remained low, while the chub mackerel population increased sharply. The chub mackerel population was depressed again in the 1980s when the Japanese sardine population expanded widely in the TWC and KOC regions. The sharp decline in the jack mackerel population in the mid 1960s was attributed to recruitment failure in association with the spawning ecosystem disturbance that took place in the very cold 1962/1963 winter as well as heavy fishing that led to a downward shift in fish body sizes (i.e., tropicalization). In the warm regime after the climate shift (1988/1989), the jack mackerel population increased again under the environment-dependent growth form. However, the abundance of the fish in the TWC region in the 1990s was still relatively low compared with that in the first

Table 2. Regional differences in recruitment of fish populations with spawning grounds in the East China Sea: the percentages of larvae and juveniles transported to the Tsushima Warm Current (TWC) and Kuroshio-Oyashio Current (KOC) regions, and the factors affecting transport, including the strength of the winter monsoon, density of the larvae and juveniles, spawning season and site, and the strength of the current systems

Climate	Oceanic conditions		Spawning nature		% entering each region		Emigration		Recruitment	
Monsoon	Front	Thermal conditions	Season	Area	TWC	KOC	TWC	KOC	TWC	KOC
Strong	Shifted to SE	Cool	Jan~Mar	SE	33	67	3	7	30	60
			Mar~May	EC	67	33	7	3	60	30
			May~July	NE	100	0	10	0	90	0
Normal	Normal position	Mild	Jan~Mar	SE	50	50	5	5	45	45
			Mar~May	EC	100	0	10	0	90	0
			May~July	NE	100	0	10	0	90	0
Weak	Shifted to NW	Warm	Dec~Mar	SE	67	33	7	3	60	30
			Mar~May	EC	100	0	10	0	90	0
			May~June	NE	100	0	10	0	90	0

Note: Spawning areas include SE (S of 27.5°N), EC(27.5°N~30°N), and NE (N of 30°N).

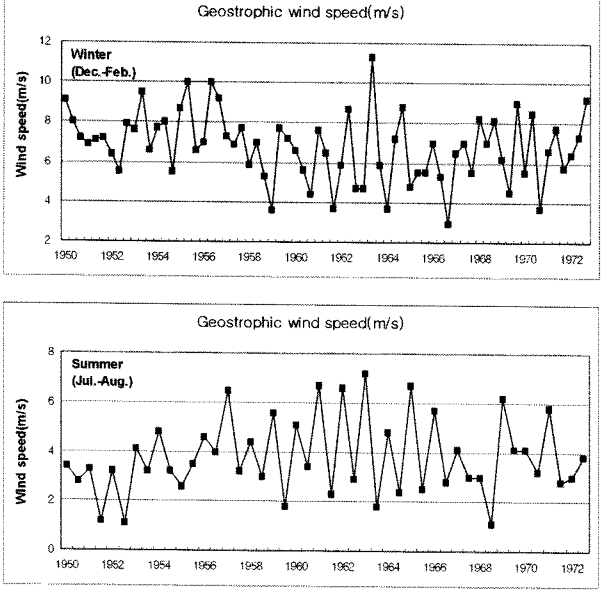


Fig. 7. Year-to-year geostrophic wind speed (m/s) in winter (DJF) and summer (JA) in the area bounded by 30°~40° N, 120°~130° E, 1950~1972 (After Nakao 1977).

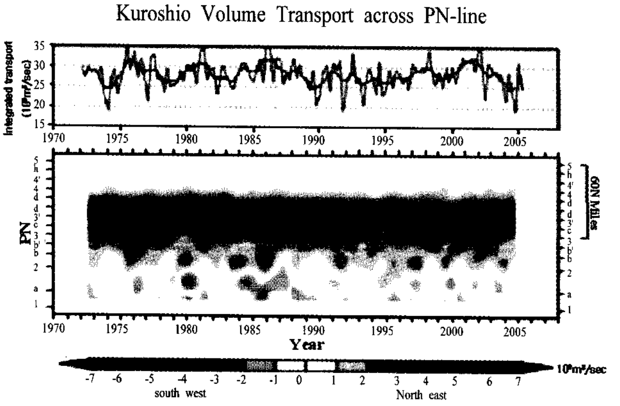


Fig. 8. Volume transport of Kuroshio across PN-line (27° 30'N, 128° 15'E~30° 00'N, 124°30'E) in the southeastern East China Sea (http://www.nagasaki-jma.go.jp/kaiyo/knowledge/kuroshio/index.html).

high period (late 1950s~early 1960s; Fig. 6c), which was attributed to the tropicalization of the fish by heavy fishing (Fig. 11).

The chub mackerel catch in the Far Eastern waters increased from the 1960s to a maximum of 2,240,000 tons in 1978, and then declined to 612,000 tons in 1990 (Fig. 6e). The chub mackerel abundance increased in the density-independent (environmental-dependent) growth form under the favorable climate-mediated ocean conditions in the 1960s, whereas the jack mackerel abundance began to decline and the Japanese sardine abundance remained extremely low.

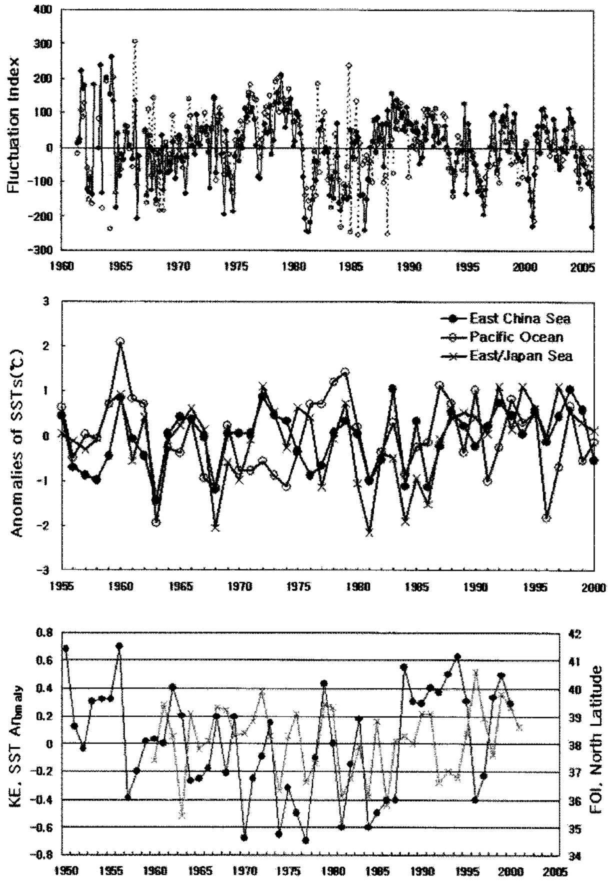


Fig. 9. Fluctuation indices of subsurface (50~100m) temperature in the southwestern East/Japan Sea (34°30'N~38°30'N, 128° 30'E ~133°30'E)(top): Anomalies of winter SSTs in the East China Sea (30°N, 126°E), western Pacific (34°N, 138°E) and southeastern East/Japan Sea (35°N, 131°E) (Uhera, Mitani 2004) (middle): Anomalies of winter SST in the Kuroshio Extension (KE) (dot) and of southern limit of First Oyashio Intrusion (FOI) (cross) (bottom) (After Gong et al. 2007).

While the biomass of chub mackerel decreased from the 1970s to the 1990s, mean body length-at-age increased in the northwest Pacific (KOC region), suggesting the density-dependant growth form. While the biomass of chub mackerel increased from the mid 1980s to the mid 1990s, the year-to-year mean body length decreased in the northern East China Sea (TWC region: 31°~36°N, 124°~132°E; Figs. 6e. and 11). We postulate that under the warm regime in the spawning and nursery grounds in the East China Sea in association with the warmer than normal temperatures and strengthened Tsushima Warm Current resulting from the consistently mild winter monsoon in the 1990s, the increased chub mackerel in the TWC region in the 1990s can be partly attributed to increased recruitment and availability to the fishing fleet, while the decreased chub mac-

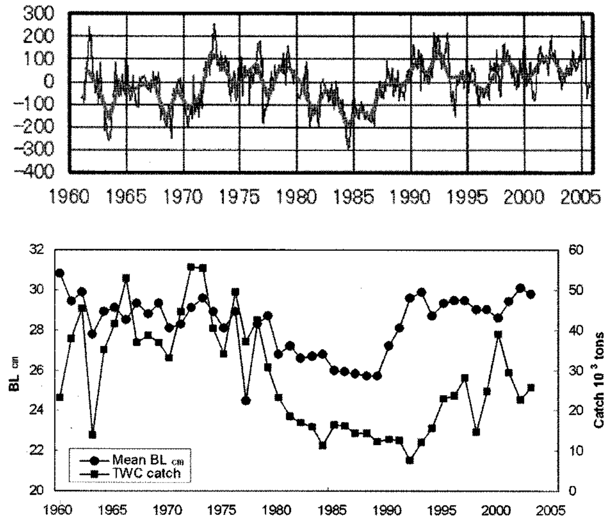


Fig. 10. Year-to-year strength of the Tsushima Warm Current (area of warm temperature>10℃) (Japan Meteorological Agency)(top) (http://www.data.kishou.go.jp/kaiyou/db/maizuru/knowledge/seiryoku.html), body length and catch of Pacific saury in the TWC region, 1960~2005 (bottom).

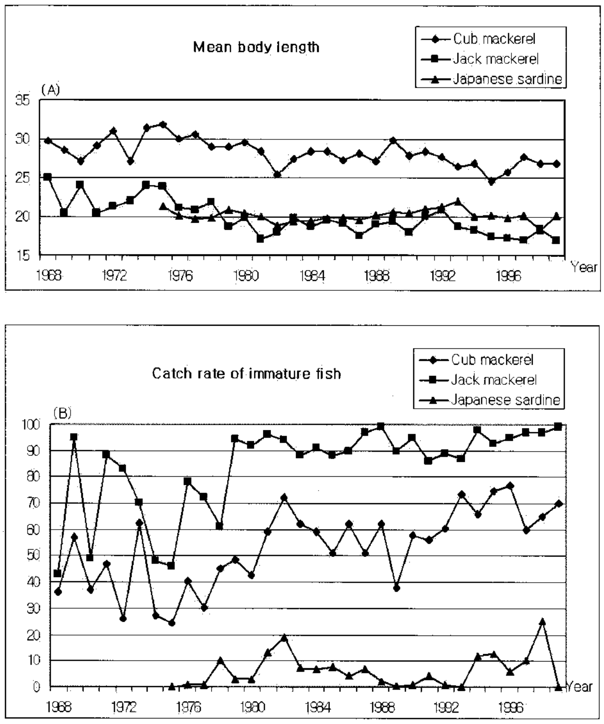


Fig. 11. Year-to-year (A) mean body length (FL) and (B) catch proportion of immature fish (percent) of chub mackerel, jack mackerel and Japanese sardine taken by purse-seiners in the northern East China Sea, Korea Strait and Yellow Sea bounded by 31°~27°N, 122°~131°E during the period 1968~2000.

kerel in the KOC region can be partly attributed to decreased recruitment and availability to the fishing fleet (Figs. 3 and 10, Table 2).

The catch time series (1910~2005) and biological measurement data indicate that the Japanese sardine population in the Far Eastern waters increased under the density-independent (environment-dependent) growth form in the 1970s when warm water prevailed in the spawning grounds and cold and productive waters expanded into the feeding grounds in the north (e.g., the Kuroshio-Oyashio transition zone in the KOC region and north of the frontal zone in the TWC region). The density-dependent length-at-age of the sardine was recognized in the TWC and KOC region during the high population biomass in the mid-1980s (Watanabe 2002, Kim et al. 2006). No tropicalization in the body size of the Japanese sardine population was identified before the sharp decline in the late 1980s. The time interval in which the pelagic fishes (Japanese sardine, chub mackerel and jack mackerel) were dominant continued for several generations, since their generation times are short (2~4 years). Density-dependent reproduction rarely induces long-term variability in pelagic fishes. The Japanese sardine abundance sharply decreased in the late 1980s due to recruitment failure in association with the regime shifts in 1988/1989 in the entire area (from the TWC to the KOC region; Fig. 11).

The abundance of the Pacific saury taken in the TWC region decreased from the mid 1970s and remained low during the cool regime in the 1980s. During the cool regime, large saury (29~32 cm fork length) did not appear in the fishing grounds in spring and summer months. After the climate regime shifts in the late 1980s (1988/1989), groups of large Pacific saury reappeared and their abundance increased in association with the warm regime in the 1990s (Figs. 3, 6f, 9, and 10).

In brief, the year-to-year and long-term regional differences in the abundance of the pelagic fish populations in the TWC to KOC regions can be explained by oscillations in the climate-induced oceanic conditions in the Far East. In fact, during deep Aleutian Lows, as in the 1980s, larval transport from the East China Sea to the KOC region increased in association with the changes in winter Asian monsoon, thermal regime and Kuroshio/Tsushima current systems , whereas larval transport to the TWC region increased during weak Aleutian Lows, as in the 1990s (Table 3).

DISCUSSION

Large Scale Current Systems in the Far East

Ocean current systems and water-mass boundaries in the region were outlined based on the previous work of Gong et al. (2006, 2007; Fig. 1).

Table 3. Climate-induced zonal oscillations of the fish abundance in the Far East before and after the climate regime shift 1988/1989

Before regime shift (1980s)	
Western sector (TWC region)	Eastern sector (KOC region)
+ MOI	+ ALPI
+ N'ly wind	+ N'ly wind
+ Winter wind drift	+ Subarctic cyclonic circulation
− Thermal front	− FOI
− Thermal regime	− Thermal regime
+ Cyclonic circulation	+ Subtropical anticyclonic circulation
− Tsushima Warm Current strength	+ Kuroshio volume transport
− Larval transport to TWC region	+ Larval transport to KOC region
− Recruitment of pelagic fish populations	+ Recruitment of fish populations
− Abundance of fish populations	+ Abundance of fish populations
After regime shift (1990s)	
Western sector (TWC region)	Eastern sector (KOC region)
− MOI	− ALPI
− N'ly wind	− N'ly wind
− Winter wind drift	− Subarctic cyclonic circulation
+ Thermal front	+ FOI
+ Thermal regime	+ Thermal regime
− Cyclonic circulation	− Subtropical anticyclonic circulation
+ Tsushima Warm Current strength	− Kuroshio volume transport
+ Larval transport to TWC region	− Larval transport to KOC region
+ Recruitment of pelagic fish populations	− Recruitment of fish populations
+ Abundance of fish populations	− Abundance of fish populations

Note; + indicates increase, strong, warm and northward.
− indicates decrease, weak, cold and southward.

Kuroshio-Oyashio Current (KOC) Region

The Kuroshio, the western boundary current of the North Pacific Ocean, flows northeastward along the continental shelf break of the East China Sea and makes a turn to the east to exit through the Tokara Strait. The Kuroshio south of Japan has been shown to follow one of two stable paths, a zonal path and a meander path. The Kuroshio Extension east of Japan is known as a highly variable current, with cold and warm rings generated from the unstable meander path. There are wide variations in the positions of the subtropical front between the Kuroshio and the transition (mixed) zone and the subarctic front between the Oyashio Current and the transition (mixed) zone. The warm Kuroshio and cold Oyashio Current converge in the waters off Hokkaido and the Tohoku district to form a transition zone with high productivity and abundance of food organisms. The location of the southern limit of the First Oyashio Intrusion (FOI) shifted further south during the cool regime in the late 1970s and 1980s in relation to the climate shifts (e.g. deep Aleutian Low Pressure) in the North Pacific (Hanawa 1995, Sugimoto et al. 2001; Figs. 1, 3, and 9).

There was a long descending trend with large annual variations for annual mean SST in the Transition Zone (TZ) and Oyashio region from 1950 to 1986, while an ascending pattern is clear in the Kuroshio region after the 1970s. Patterns of variation in the SST for the TZ and Oyashio region are similar, but differ from that in the Kuroshio, indicating that two different ocean systems affect the Kuroshio and the Oyashio regions (Tian et al. 2003). However, the difference in the SST in the north and south also seems to be related to the circulation patterns. The subtropical anticyclonic circulation will be enhanced in association with strong subarctic cyclonic circulation during the deep ALP. Therefore, the SST in the south (Kuroshio region) will be warmer than normal when the SST in the north (Oyashio region) is cooler than normal as in the 1980s.

Tsushima Warm Current (TWC) Region

The warm and saline Kuroshio branch overlaid with fresh shelf water enters the East/ Japan Sea through the Korea Strait as the Tsushima Warm Current (TWC). The most westward stream of the TWC, known as the East Korean Warm Current (EKWC), flows northward along the east coast of Korea up to about 38°N~39°N, where it meets the southward flowing North Korean Cold Current (NKCC, an extension of the Liman Cold Current: LCC). At the confluence, the currents flow away from the coast and flow east to the Tsugaru Strait along the subpolar Front. The transport of inflow from the TWC to the Korea Strait varies considerably, but the annual mean transport is $2 \times 10^6\ m^2\ s^{-1}$, with minimum transport in winter and spring and a maximum in autumn (Huh 1982). Much of the flow (70~90%) flows out through the Tsugaru Strait, while the rest continues north to enter the Okhotsk Sea through the Soya Strait.

There are wide variations in the positions and contours of the front, not only from season to season but also for same month in different years. The year-to-year variation in the positions of the frontal zones in the west is higher than that in the eastern East/Japan Sea, which indicates the instability of the warm and cold current systems along the continent (Gong et al. 2006).

The existence of the EKWC is very variable and hence the position of the subpolar front also varies. The EKWC was weak or absent in the southwestern East/Japan Sea in spring and early summer 1981, when the main flow of the TWC shifted to the southeast. A deeper mixed layer depth (MLD) and colder-than-normal mixed layer temperatures (MLT) were recognized in the PM line (36°N, 136° E~41° N, 132° E) in 1977, 1981 and 1985/86, while a deeper MLD and warmer-than-normal temperature were noticed in 1988 (Kim and Isoda 1998).

Intensification of the Aleutian Low system strengthened the wintertime East Asian monsoon over Siberia and the northern East/Japan Sea. The strong westerlies cooled the surface water of the northern East/Japan Sea and facilitated subduction of cold water below the Tsushima Warm Current. Springtime solar radiation increased during the 1980s. These conditions led to enhancement of stratification between subsurface and surface waters in spring, limiting the nutrient supply on the surface to the extent that a summer-adapted plankton community was favored (Chiba and Saino 2002).

Therefore, zooplankton biomass decreased south of the subpolar front in spring and north of the front in the East/Japan Sea in summer in the late 1970s and 1980s, which must have been detrimental to the growth of pelagic communities such as anchovy, Pacific saury and common squid during their feeding migrations (Gong et al. 2006).

East China Sea and Yellow Sea

The monsoon regime that prevails over the Yellow Sea, East China Sea, and Korea Strait provides a fundamental rhythm to regional oceanographic processes. In particular, winter outbreaks of polar continental air over the region are the most severe in the world. Atmospheric forcing occurs in two modes: in winter by cooling and destratification due to strong cold and dry northerly winds, and in summer by extensive precipitation, river runoff, and solar heating, which produce a well-stratified water column with a warm, low-salinity surface layer. Regional bathymetry and topography are important influences on the oceanographic response to atmospheric and oceanic forcing (Figs. 1 and 2).

The surface circulation is strongly influenced by the monsoonal wind system, the Kuroshio-Tsushima-Yellow Sea Warm Current System and the complex regional geography (i.e., the distribution of land masses, water depths, and major rivers; Huh 1982). Winter cooling of the shelf waters may also depend on water depth, resulting in a differentiation of surface temperature between shallow and deep waters. The distribution of temperatures in the East China Sea and Yellow Sea in winter is similar in pattern to the bottom topography (Fig. 2, NOAA's infrared imagery and bottom topography). In winter, the maxima of wind speed appeared in the years of 1953, 1956, 1963 and 1968. Particularly strong winter monsoon winds in 1963 forced a remarkable northward flow of warm water in the east-central Yellow Sea and an extreme southward flow of cold water in the western Yellow Sea and the East China Sea resulting from a strengthening of natural circulation in this region of semi-closed seas with a warm influx in the southeast side (the Yellow Sea Warm Current; Huh 1982).

The thermal shelf front between the Kuroshio-Tsushima Current system and the Chinese Costal Water is shifted to the central East China Sea in winter by the strong northerly winter monsoon. The annual cycle of monsoon winds in this region is driven by the thermal contrast between the Eurasian continent and the Pacific Ocean. The cyclonic circulation in the East China Sea and Yellow Sea might be affected by the strong winter monsoon. Then the volume of water brought by the Kuroshio from the southern East China Sea to the Pacific side will increase (increased volume transport at the PN line). The expansion of Yellow Sea Warm Current water in the eastern Yellow Sea will increase while the Tsushima Warm Current strength in the Korean Strait and East/Japan Sea will be weakened (Figs. 8 and 10).

Broad tidal currents are important features of the Yellow Sea coastal regions. The Yellow Sea and the East China Sea are productive continental shelf regions, with an average primary productivity of 300 gC m^{-2} y^{-1}. The shelf-break regions of the East China Sea are important spawning grounds for the warm water fish species. There is no biological winter in the East China Sea because the PAR is not a limiting factor for primary production in winter.

Ocean-Current-Mediated Migration Circuits of the Pelagic Fish Populations

① The ocean current in the Far East region shows a sharp boundary between the warm and cold water systems and the winter sea surface temperature reflects the importance of the shifts in wind resulting from the winter monsoon, which control the transport of fish larvae and juveniles to different regions (Figs. 1 and 2).

② Hypothetical migration circuits of Pacific herring, Japanese sardine, Japanese anchovy, jack mackerel, chub mackerel, Pacific saury and common squid in the Far East were developed based on the ocean current systems, nature of spawning, larval drifts and fishing information (Pacific herring: Naumenko 2002, Tang 1991, Gong 1973, Tanaka 2002; Japanese sardine: Nakai 1962, Hiyama 1998, Ito 1961, Kuroda 1991a,b, Nishimura 1965, Schwartzlose et al. 1999, Wada and Jacobson 1998, Yatsu et al. 2005, Zhigalin and Belayev 1999; Japanese anchovy: Chang et al. 1980, Chikuni 1985, Iversen et al. 1993, Nakamura et al. 2005, Takahashi and Watanabe 2005, Tanaka 1979, Zhu 1991; jack mackerel: Yamanaka et al. 1988, Zhang and Lee 2001, Uehara and Mitani 2004, Yoda et al. 2004, Yoda and Sassa 2004, Sassa et al. 2006, Uehara et al. 2006; chub mackerel: Iizuka and Hamasaki 1983, Novikov 1977, Takeshita and Hayashi 1991, Watanabe and Yatsu 2006, Wang 1991, Yamaguchi 1988, Yatsu et al. 2005; Pacific saury: Novikov 1967, 1972, 1982, Sablin and Pavlychev 1982, Gong 1984, Gong and Suh 2003, 2004, Shuntov 1967, Tian et al. 2003, 2004, Nishimura 1969, Kosaka 2000, common squid: Gong et al. 2006, Murata 1991, Kasahara 1991, Nakata 1993, O'Dor and Coelho 1993, Fig. 4a~g).

Migration circuits of the pelagic fish populations are similar in pattern to the ocean current systems, which suggests that the distribution of the fishes is very much controlled by the currents and that the fish populations are affected by the current systems (Figs. 1 and 4). Variation in the migration circuits of the pelagic fishes is mediated by the effects of climate changes on the current system in the Far East (Gong et al. 2007).

Biology and Habitats of Pelagic Fish Populations

Pacific Herring

Pacific herring, *Clupea pallasii,* inhabit oligohaline cold waters (0~7℃) along the northern coast of the Asian continent. The herring in the northwest Pacific west of 180° (FAO statistical area 61) have been separated geographically into 6 marine groups but it appears that genetic mixing among groups might be common (Chikuni 1985, Naumenko 2002). The herring inhabit cold water below the permanent thermocline (50~250 m) in the southern East/Japan Sea and cold water below the seasonal thermocline in the Yellow Sea (Gong 1973, Tang 1991). Herring in the Yellow Sea reached maturity at a younger age (2 years) than did those in the northern marine groups (2~4 or 4~6 years; Table 1).

Patterns of fluctuation in abundance of Pacific herring were out of phase with those of Japanese sardine (Kawasaki 1991, Kawasaki and Mori 1995, Mori and Kawasaki 1995; Fig. 6a, b). Pacific herring were abundant during cool periods associated with the deep Aleutian Low. The Sakhalin-Hokkaido group were the dominant fish in the region in the mid 1870s and mid 1920s (Hanamura 1963). Researchers have suggested that warming of the sea was responsible for the drastic declines in abundance of the group in the late 1930s and 1950s (Chikuni 1985, Tanaka 2002). Pacific herring, like yellow crocker and pollock, has been a major target of Korean fisheries since the 15th century (Park 1976). The Pacific herring in the Yellow Sea have been heavily exploited by Chinese fishermen since 1968. The Chinese herring catch amounted to 180,000 tons in 1972, while the Korean catch was negligibly small. Most of the catch from the TWC region in the early 1970s was by Chinese fisheries (Fig. 6a).

The Japanese sardine

The Japanese sardine, *Sardinops melanostictus,* is distributed along the coast and offshore in the northwestern Pacific and its adjacent regions (28°~55°N, 120°~160°E). The fish inhabit the upper layer (0~200 m) with a temperature range of 10~20℃ (optimum range 13~15℃). Japanese sardines feed mainly on phytoplankton while the other pelagic fish species almost exclusively feed on zooplankton. Spawning of Japanese sardine occurs year-round but peaks in November-March in the southern regions of the population's range (the northern East China Sea and its adjacent regions). Spawning is followed by a feeding migration to the north and offshore on the Pacific side and in the East/Japan Sea in summer. Mature sardines return to the spawning grounds in winter, while immature fish tend to remain in the southern part of the feeding grounds to over-winter. When abundance was high, the feeding grounds expanded into the northwestern Pacific (off Hokkaido) in the KOC region and to the northwestern East/Japan Sea in the TWC region (Nakai 1959, Park 1978, Watabe 1992a, 1992b, Kawasaki 1993, Wada and Jacobson 1998, Gong et. al. 2007; Fig. 4b). The distribution ranges of the Japanese sardine and Japanese anchovy extended from the coastal to offshore waters during periods of high abundance (Takahashi and Watanabe 2005), suggesting the high possibility of intermixing between adjacent subpopulations (Okazaki et al. 1996, Gong et al. 2007).

Japanese anchovies

Japanese anchovies, *Engraulis japonicus,* have a stronger preference for inshore warmer waters than other pelagic fishes (Nishimura 1969, Kawai 1995, Ogawa and Nakahara 1979, Gong et al. 2007). The anchovies are distributed in the upper layers (0~100 m) with water temperature 10~28℃ (optimum 17~24℃; Table 1). They are transported to the open ocean by the Kuroshio Current in the Pacific (Funamoto and Aoki 2002) and by the Tsushima Warm Current in the East/Japan Sea and Yellow Sea (Nishimura 1965; Fig. 4c). Anchovies are a typical r-selected species characterized by small size (14 cm), rapid growth, early maturity (1 year) and short life span (4 years). Anchovies are small pelagic plankton feeders, and are prey for some 30~40 important higher-trophic-level species (e.g., Spanish mackerel, chub mackerel, hair tail etc.). Previous researchers have suggested that fast-growing anchovies in the metamorphosis stage (20~35 mm in standard length) can survive better in the Kuroshio-Oyashio region (Takahashi and Watanabe 2004). Jin and Tang (1996) attributed the sharp increase in anchovy abundance in the northern East China Sea in the 1990s to changes in community structure. The depletion of most demersal and large piscivorous pelagic fishes resulted in an increase in the abundance of small planktivorous pelagic fishes in the Yellow Sea in the 1990s (Jin and Tang 1996). However, Yellow Sea anchovy landings by Chinese pair-trawlers declined from 1,200,000 tons in 1989 to 480,000 tons in 2001 (Zhao et al. 2003). The high chub mackerel abundance in the TWC region in the 1990s seems to be partly attributable to the increased anchovy abundance, as anchovies are food for chub mackerel (Fig. 6c, e).

Jack mackerel

Jack mackerel, *Trachulus japonicus,* inhabit warm (10～25℃, but mostly 15～20℃) and haline (34.0～34.7 psu) coastal and offshore waters from the surface to the 150 m layer (Nishimura 1969, Kawai 1995, Gong et al. 2007). No jack mackerel are found in the cold current systems of the East/Japan Sea and the Oyashio waters (Figs. 1 and 4d). Jack mackerel in the Far East region are known to have a life span of 6～7 years and to grow to 16～18 cm (FL) in the first year, to 23～25 cm in 2 years (fully mature) and to 28～39 cm in 3 years (Table 1). Spawning takes place in the haline, warm waters along the eastern edge of the continental shelf of the East China Sea (Kawai 1995, Yoda and Sassa 2004, Sassa et al. 2006). Jack mackerel in the area (FAO 61) are divided into two or three subpopulations: (1) the Tsushima Warm Current subpopulation in the East China Sea, Korea Strait and the waters off western Japan, and (2) the Pacific subpopulation in the East China Sea and the waters off southeastern Japan (Uehara and Mitani 2004). Jack mackerel inhabiting the TWC region and KOC region both have their main spawning grounds in the East China Sea and a small local area in the north (stocklet), which suggests a strong possibility of interchange between the jack mackerel in the TWC and KOC regions. Therefore, the jack mackerel in the Kuroshio/Tsushima Current System in the Far East should be considered as a single population for management purposes.

Jack mackerel have quite large spawning grounds and the nursery grounds for juveniles are close to the spawning grounds. Most of the larvae and juveniles and spent adults are transported by the ocean currents from the spawning grounds to the nursery and feeding grounds in the north of their distribution ranges, and then return to their source area in autumn and winter (Gong et al. 2007, Nishimura 1965, Sassa et al. 2006) because the production systems are active in the south even in meteorological winter. However, the number of jack mackerel emigrating from the East China Sea is small relative to the other pelagic fishes since the fish prefer the warmer waters in the south.

Chub mackerel

Chub mackerel, *Scomber japonicus,* inhabit the pelagic zone in summer and the mesopelagic zone in winter. Juvenile fish inhabit warm waters (14°～21° C), whereas adults inhabit mild waters (12～16° C), leading to the general observation that bigger fish live in deeper waters (Nishimura 1969, Cushing 1969, 1975, Kawai 1995, Gong et al. 2007). The chub mackerel is widespread in the Far East (25～48°N, 120～170°E). The age at first maturity is estimated to be 2～3 years, varying slightly by region and with abundance. Spawning takes place from the south-central East China Sea (Feb～Mar) to the northern East China Sea (Apr～June), the southern East/Japan Sea, and the waters off central Japan in the Pacific (May～July). After spawning, adults and their offspring migrate northeast and are distributed throughout the feeding grounds in the Kuroshio-Oyashio transition zone and the Oyashio Current as well as in the Yellow Sea and the East/Japan Sea, and mature fish migrate further south to the spawning grounds around southern Japan and East China Sea (Nishimura 1965, Novikov 1977, Wang 1991, Watanabe and Yatsu 2006, Gong et. al. 2007). The chub mackerel abundance in the KOC region decreased sharply during the sardine-dominant period in the 1980s, but remained fairy high in the TWC region and increased again in the 1990s: an unusual increase in abundance in the sequence of species alternation (Nakahara and Ogawa 1978, Ogawa and Nakahara 1979, Matsuda et al. 1991, Watanabe and Yatsu 2006, Gong et al. 2007). The increase in chub mackerel abundance and smaller increase in jack mackerel abundance in the early 1990s suggest inter-specific competition between the two species in the TWC region.

There is an intimate correlation between animal communities and the water masses they inhabit. Japanese anchovies originate in tropical and subtropical communities and inhabit the superficial waters in the Far East. Jack mackerel and young chub mackerel belong to sub tropical-temperate communities and inhabit warm, haline waters. Adult chub mackerel and Japanese sardines originated from temperate communities and inhabit mild or cool waters. Ogawa and Nakahara (1979) suggested that chub mackerel and Japanese sardine were the dominant species during mild or low-temperature periods and that jack mackerel and anchovy prevailed during high-temperature periods. Fluctuations of jack mackerel and anchovy populations are relatively stable, while fluctuations in the abundance of the anti-tropical species such as Pacific herring and Japanese sardine are of high amplitude (Watanabe 2003).

Pacific saury

Pacific saury, *Cololabis saira,* inhabit haline (33.6～34.8 psu) and mild (10～20℃, optimum 13～19℃) surface waters. These fish are found in the upper mixed layer and belong to the Okaba Community-Ⅱ group. The life span of Pacific saury is very short (1～1.5 years) and the age at maturity is 1 year (20 cm in fork length). The fish are distributed in the highly haline open sea (25～55°N, 125～170°E) and spawn across a large area (30～45°N, 125～160°E) from autumn to spring. Pacific saury spawning starts in the Kuroshio-Oyashio transition zone and the southern East/Japan Sea in autumn, and moves to the Kuroshio area and the East China Sea in winter, and then back to the transition zone in the northwestern Pacific and the Subpolar frontal zone in the East/Japan Sea in spring (Fukataki 1966, Odate 1977, Watanabe and Lo 1989, Watanabe et al.1997, Ito et al. 2002, Gong 1984, Gong and Suh

2003, 2004).

Pacific saury have been fished mainly by gillnet and set net during their northward (spawning and feeding) migration in spring and summer and southward (wintering and spawning) migration during autumn and winter in the East/Japan Sea (TWC region), while they have been fished mainly by stick-held dip-net during their southward (spawning) migration in autumn in the northwestern Pacific (KOC region) since 1949 (Fukataki 1966, Fukushima 1979, Gong 1984, Kosaka 2000, Gong and Suh 2004, Gong et al. 2007). The catch trends for Pacific saury during the period 1907~2000 in the northwest Pacific revealed that their abundance was high in the early 1910s, 1920s, 1950s and 1990s. The decadal variations in abundance corresponded well with the climate regime shifts of 1976/1977, 1988/1989 and 1997/1998. The fish are sensitive to ecosystem changes such as changes in thermal regime and plankton biomass. Large-sized saury (mode of 29~30 cm) appeared in the northward feeding migration in the spring and summer in the TWC region during warm regimes as in the 1960s and 1990s, while they were apparently absent during cold regimes as in the 1980s when overall population abundance remained low (Figs. 6f and 10). Researchers have suggested that no density-dependent effect on growth is evident and that recruitment success and growth of the fish are affected by oceanographic conditions (Gong and Suh 2004, Tian et al. 2004).

Common squid

Common squid, *Todarodes pacificus,* are distributed from the East China Sea to the Yellow Sea, East/Japan Sea and the northwest Pacific (Fig. 4g). The squid belong to the Okaba Community-II and inhabit the euryhaline and eurythermal waters (7~23℃, 12~18℃). The life cycle of the common squid is annual and nearly semelparous with a peak spawning period in the East China Sea from autumn to winter, and are most abundant in the East/Japan Sea (TWC region) and the Tohoku region of the northwest Pacific (KOC region; Sakurai et al. 2000, Gong et al. 2007). A portion of the common squid caught by jigging fishing in the East/Japan Sea (TWC region) in the 1960s and 1970s was landed at the fishing ports along the northwestern Pacific coast (KOC region). These squid were included in the TWC region in our time series of squid catch. In our revised regional catch calculations for the Pacific side (KOC region; Fig. 6), the squid abundance in the KOC region was extremely low in the 1970s and the 1980s. The mechanism promoting the changes in structure, distribution, and abundance of the common squid population is related to the ocean current-mediated migration circuits, as phenological variables (e.g., timing and migration ranges, growth rate and fecundity) respond to climate shifts (Gong et al. 2007).

Fishing Methods, Monthly Catch Rates and Fishing Grounds Off Korea

The catch and catch per unit fishing effort (CPUE) for the period 1960~2006 are based on fishing using the most commonly employed fishing gear for the species: purse seine for chub mackerel, jack mackerel and Japanese sardine; gill-nets for Pacific saury in the waters off Korea and stick-held dip nets in the northwest Pacific by the fleets from Japan, Korea, Taiwan and Russia; dragnet and set-net for anchovy; and jigging and trawling for common squid. The time series of catch and catch per unit fishing effort (CPUE) for the three species (jack mackerel, chub mackerel and Japanese sardine) taken by the Korean purse seine fishing fleet for the period 1970-2004 revealed the same fluctuation patterns and were significantly positively correlated (NFRDI 2005). The time series for jack mackerel catch from the TWC region and CPUE (tons/set net) for set net fishing along the Japanese coast showed the same trends during the period 1952~1998 (Hasegawa 2000). Therefore, the time series of catch was employed as an index of long-term fluctuations in the population abundance.

Chub mackerel, jack mackerel and Japanese sardine have been fished mainly by Korean, Japanese, and Chinese purse seiners in the East China Sea and its adjacent regions since the 1920s. The jack mackerel fishing grounds have covered most of the spawning grounds in recent years (Yoda et al. 2004). Most of the Korean jack mackerel landings are incidental bycatch of Korean purse seiners targeting chub mackerel in the Korea Strait and southwestern Yellow Sea. The major concentrations of jack mackerel, however, were found in the Korea Strait in spring (April~July) and autumn (October~January), while those of the chub mackerel were in the waters off southwestern Korea in autumn (September~December) in the 1990s and recent years.

Most of the seven fish species landed by the Korean fishing fleet are fished during the northward (feeding) migration in spring and the southward (spawning~wintering) migration in autumn, suggesting that the Korean fishing fleet covers only small part of the distribution ranges (Fig. 4. a~g). Therefore, we included fishing records from Japan, China/Taiwan and Russia in our estimates of regional catch (abundance) trends for the TWC region (Fig. 6).

Changes in Abundance (Catch) of the Pelagic Fish Populations

In the time series of jack mackerel catch from the Japanese fishing records, a negative correlation was found between the catch in the TWC region and that in the KOC region, especially during the abundant periods in the 1960s~1990s (Uehara and Mitani 2004). In our updated time series for the jack mackerel catch, in which the catches from Korea and Taiwan are included in the TWC region (Fig. 6d), two points are noted: (1) the catch from the TWC region dropped when the catch from the KOC region increased in the years 1952, 1963, 1868, 1970, 1986 and 1996, and (2) the total catch (TWC+KOC regions) dropped in the years when the catch shifted from the TWC to the KOC region. From the first point, it is postulated that there must be regional oscillation of recruitment from the same source area. The drop in the total catch in the years of regional oscillation from the TWC to KOC region suggests that a disturbance in the production system in the source area in the East China Sea, resulting in reduced availability to the fishing fleets.

Zonal Differences in Recruitment by Monsoon and Current-Mediated Larval Transport

The regional rates of recruitment of fish in the early life stages (e.g., jack mackerel larvae) from the spawning grounds in the East China Sea to the TWC and KOC regions were estimated on the basis of following factors: (1) water-mass boundaries (thermal front or salinity front) and thermal conditions in the spawning grounds, which can be shifted by climatic factors (e.g., winter monsoon), (2) the spawning nature (season and area), which can be shifted by wind stress and thermal conditions, (3) the density of the larvae and juveniles, (4) the strength of the current systems, and (5) the migration circuits of the fishes, which can be distorted by changes in the ocean current systems.

During periods with normal ocean climate conditions, larvae and juvenile fish produced or occurring in the southern East China Sea (SE; south of 27° 30'N) in winter (January~February) are mostly transported to the KOC region because they are carried to the Kuroshio region by the wind drift. However, many of the larvae and juveniles occurring in late winter/early spring (March) are transported to the TWC region because of seasonal changes in wind direction. Therefore, total transport rates of the fish to the TWC and KOC are estimated to be equal (i.e., 50% of fish are transported to the TWC, 50% to the KOC). However, the emigration rate from the fishing grounds in the KOC region will be higher than that from the TWC region because of the boundary-free open ocean off of the southern Kuroshio region in the Pacific.

In summary, under normal ocean climate conditions, larvae and juveniles occurring in the eastern central (EC; 27° 30'N~30°N) and northeastern (NE; north of 30°N) East China Sea during the spring months (March~May) are mostly transported to the TWC region. About 80% of the fish are transported to the TWC region and the reminder (~20%) enter to the Pacific (KOC region); some fish in the KOC region then emigrate, thereby becoming unavailable to the fishing fleets (Table 2).

During abnormally cool regimes associated with strong winter monsoons as seen in the 1980s, larvae and juveniles are transported to the KOC region from SE and EC East China Sea in winter (January~March) and even in spring months (March~May) at higher rates than are observed during the normal-mild regime due to the southward shift of the bifurcation of the Tsushima Warm Current from the Kuroshio (around 30°N, 128°E, west of Amami Oshima Island). About 70% of fish from all of the spawning grounds are transported to the KOC region and about 30% are transported to the TWC region. However, the rate of emigration from the fishing grounds in the KOC region will be higher than that from the fishing grounds in the TWC region due to the strong northwesterly wind toward the open ocean of the Pacific.

During abnormally warm regimes associated with weak winter monsoons, as in the 1990s, most fish in the early life stages (~90%) produced in the East China Sea feed around the spawning grounds or migrate to feed to the northern areas including the Korea Strait, the southeastern East/Japan Sea and the Yellow Sea. Only an estimated 10% are transported to the KOC region, some of which are not available to the fishing fleets.

The abundance of the fish populations with warm-water origins (anchovy and jack mackerel) is higher in the TWC region than the KOC region during the mild and warm regimes associated with weak winter monsoons as in the late 1950s and the 1990s. Chub mackerel populations are abundant during mild or cool regimes, as in the 1970s, and the abundance of fish (especially jack mackerel and chub mackerel) in the TWC region in the 1990s was higher than that in the KOC region in association with favorable environmental conditions.

Climate-Shift-Induced Marine Ecosystem Changes

Winter-monsoon-induced year-to-year regional differences in fish abundance

It seems likely that many factors, including biological factors, environmental factors, density dependant factors, inter-specific relationships with other species, and the production systems in the spawning and feeding grounds are involved in producing annual fluctuations in the pelagic fish populations. The year-to-year regional differences in the recruitment of the jack mackerel juveniles transported by the currents apparently result from the negative correlation between the regional catches, the effects of the winter monsoon, and the spawning site and season. The long-term fluctuations in the abundance of the jack mackerel as well as the chub mackerel, Pacific saury, and Japanese sardine can be explained on the basis of current-mediated recruitment, changes in the climate-induced thermal regime and changes in the body size distributions of the fish populations.

Ocean climate changes in the Far East can be monitored using several climate indices such as the AOI, ALPI and MOI. The AOI is defined as the leading empirical orthogonal function (EOF) of winter time sea level pressure (SLP) poleward of 20℃N, and is largely associated with the variability in the mid-latitude North Pacific (Thompson and Wallace 2000a, 2000b). The MOI is defined as the difference in the SLP between Irkutsk (Russia) and Nemuro (Japan), and represents the conditions of the winter Asian monsoon (Tian et al. 2004).

Climate-shift-induced decadal-scale regional differences in fish abundance

Climate shifts influence marine ecosystems. The Aleutian Low Pressure Index (ALPI) co-varies not only with the Pacific North American pattern, but also with the Arctic Oscillation (AOI) and Asian Monsoon (MOI) (Thompson and Wallace 2000a, 2000b, Tian et al. 2004, 2006). Cool regimes in the Kuroshio-Oyashio transition zone might be due to intensified westerly wind caused by the deep Aleutian Low Pressure and the Arctic Oscillation. In the period 1900-1997, the ocean climate regime appears to have shifted around 1925, 1947 and 1976 (Minobe 1997). In the time series of SSTs, regime shifts were detected in 1925/1926, 1945/1946, 1957/1958, 1970/1971, 1976/1977, 1988/1989 and 1998/1999 (Yasunaka and Hanawa 2002). The First Oyashio Intrusion (FOI) shifted to the south in association with the deep Aleutian Low during the 1970s～1980s (Fig. 9; Ogawa et al. 1987, Hanawa 1995, Nihira 2005, Tian et al. 2004, 2006).

The Kuroshio volume transport might be increased in association with the strengthened anticyclonic circulation in the subtropical Pacific (KOC region) during periods of deep ALP. The cool regime will be intensified on the continental side (Yellow Sea, East China Sea, and East/Japan Sea; TWC region) by the enhanced winter monsoon (MOI), which co-varies with the ALP. Therefore, the strength of the Tsushima Warm Current system and its temperature anomalies were far bellow normal in the 1980s.

When the strength of the Tsushima Warm Current in terms of warm (>10℃) water area in the East/Japan Sea was below the long-term mean, the volume transport of the Kuroshio in the southern East China Sea (PN line; 27° 30N, 128° 15'E～30° 00'N, 124° 30'E) was above the long-term mean in the 1980s (Figs. 8～10). We postulate that the rate of larval transport from the East China Sea to the Northwest Pacific side (KOC region) increased as a result of the increased Kuroshio volume transport during the abnormal southward shifts of First Oyashio Intrusion (FOI) associated with the deep ALP in the 1980s.

Conversely, the strength of the Tsushima Warm Current and its temperatures were above the long-term mean in the warm regimes after climate regime shifts (1988/89) under the weak winter monsoon, which co-varied with the weak Aleutian Low, when the Kuroshio volume transport in the East China Sea was weaker than normal (Figs. 8 and 9). Therefore, during warm periods (e.g., the 1990s) the rate of larval transport to the TWC region increased while that to the KOC region decreased, resulting in an increased abundance of warm-water-origin pelagic fish populations such as chub mackerel, anchovy, Pacific saury, and common squid in the TWC region as cool-water-origin fishes such as Japanese sardine and Pacific herring were replaced by warm-water-origin pelagic fishes. For example, sardines were replaced by four other species in 1988, when sardine recruitment failure occurred.

Fishing-Induced and Density Dependent Effects on the Pelagic Fish Populations

Body length is an important fish characteristic that affects a species' ecology (e.g., predation, competition, trophic level, mortality, longevity), variability, fishing characteristics (gear size selectivity), and management. Therefore, we paid special attention to the length structure and the length and age at maturity of jack mackerel, chub mackerel and Japanese sardine populations, which have been exploited mainly by the purse seine fishing. Heavy fishing in non-tropical waters can tropicalize fish stocks, in the sense that it drives them to exhibit the characteristics of their tropical counter parts (i.e., smaller body sizes and earlier maturation; Pauly 1998, Stergiou 2002).

The mean body length of the chub mackerel making up the catches in the TWC region has decreased from about 30 cm in the early 1970s (an abundant period) to 26 cm in the early 1990s (a low abundance period). The proportion of immature chub mackerel in the catch increased sharply after the climate regime shift of 1977/1978 and remained high during the 1980s and 1990s. The mean body length of the jack mackerel in the catch decreased from about 23 cm in the late 1960s (a high abundance period) to 19 cm in the early 1980s (a period of low abundance). The proportion of the jack mackerel catch consisting of immature fish increased to 90% after the 1977/1978 climate regime shift and thereafter remained high in the 1980s and 1990s. No density-dependent effects are evident in the time series of mean body sizes during the high abundance period for chub mackerel (the 1970s and 1990s) and jack mackerel (the late 1960s～early 1970s, 1990s) in the TWC region. We postulate that density-dependent effects are masked by tropicalization in the body sizes of chub mackerel and jack mackerel under heavy fishing pressure in the East China Sea. There were apparent shifts from favorable to unfavorable conditions for chub mackerel during 1976～1977 and 1985～1986, and from unfavorable to favorable during 1969～1970 and 1988～1992 (Yatsu et al. 2005).

The mean body length of the Japanese sardine decreased from 20～21 cm in the late 1970s to 19～20 cm in the early 1980s (an abundant period) and then steadily increased to about 21～22 cm in the early 1990s (a depleted period), suggesting a density-dependent effect during the abundant period of the sardine population in the TWC region (Fig. 11). The body length-at-age of the sardine inhabiting the East/Japan Sea and northern East China Sea (TWC region) has been described as varying in a density-dependent manner (Watanabe et al. 2002, Kim et al. 2006). Density-dependence of length-at-age was also identified in the KOC region (Watanabe et al. 2002). However, the dominant periods for the seven study species lasted for 10～20 years, which encompassed several generations for Japanese sardines and other pelagic fish species (Ogawa and Nakahara 1979, Ogawa et al. 1987, Gong et. al. 2007). The generation time of the sardine is about three or four years. Therefore, density-dependant reproduction rarely induces long-term variability in the pelagic fishes (Matsuda et al. 1991, 1992). Kuroda (1991) suggested that the abundance of the sardine fluctuates periodically as a result of natural changes rather than fishing pressure.

Several researchers have suggested that there is a close relationship between interdecadal ocean climate variability and sardine populations (Tomosada 1988, Watanabe et al. 1995, Noto and Yasuda 1999). Environmental conditions were favorable for sardines in 1969～1987 and unfavorable in 1951～1967 and after 1988 (Yatsu et al. 2005). The population decline after 1988 may have occurred as a result of the abrupt increase in SST since 1988 in the Kuroshio Extention region (Noto and Yasuda 1999). Therefore, the environment in Kuroshio Extension region is regarded as a leading factor affecting the sardine biomass, while the density effect makes a secondary contribution (Noto and Yasuda 2003).

The average body size of Pacific saury was small in spring and summer (during the northward feeding migration) in the 1980s when the catch was mainly of medium-sized (26～27 cm) fish and the abundance declined to the lowest level recorded in the TWC region (Fig. 10). The disappearance of large sized (29～32 cm) fish in the TWC region in the spring catch is attributed to recruitment failure resulting from unfavorable spawning conditions for spring spawning. The disappearance of large (29～32cm) fish from the autumn catch in the Tohoku region (KOC region) in the late 1960s, when the catch consisted mainly of fish all around 26～27 cm in length, was attributed to unfavorable spawning conditions for autumn spawning (Novikov 1982).

After a climate regime shift in 1988/1989 the catch consisted of two size classes in the TWC region: autumn-bred (24～28cm) and spring-bred (29～31cm) fish (Fig. 10). The population structure and abundance of the Pacific saury returned to normal after the climate shift in the late 1980s. However, the catches were lower in the 1990s because of the limited fishing activity (Oozaki et al. 1998, Gong and Suh 2004, Gong et al. 2007). The catch per unit fishing effort (CPUE) for the Pacific saury from stick-held dip-net fishing in the northwest Pacific Ocean sharply increased as the recruitment of Japanese sardines sharply decreased in association with the climate regime shifts in the late 1980s (Watanabe 2007), suggesting the replacement of the sardine by the Pacific saury (Gong et al. 2007).

Alternation of Dominant Pelagic Fish Species and Regional Differences in the KOC and TWC Regions

During the period 1910～2004, an orderly alternation of dominant species was observed in the northwest Pacific (KOC) and the Tsushima Warm Current (TWC) regions. After the collapse of the herring fishery in the late 1920s, the Japanese sardine dominated in the 1930s, Pacific saury, jack mackerel, common squid and anchovy (four species) in the 1950s～1960s, herring again in the late 1960s ～early 1970s, chub mackerel in the 1970s (after increasing from the mid-1960s) and then the sardine again in the 1980s (after increasing from the mid 1970s). As sardine biomass decreased in association with the climate shifts in the late 1980s, abundance of the four species increased immediately in the warm regime from the late 1980s to the 1990s (Gong et al. 2007).

A large regional difference in abundance between the TWC and KOC regions (TWC>KOC) was identified in the time series of catches of Japanese anchovy, chub mackerel, jack mackerel and common squid, in particular, during the 1990s. Gong et al. (2007) suggest that the regional difference in amplitude (catch) in the long-term fluctuations of the above seven pelagic fish species is attributable to both availability and fishing nature and activities (Gong et al. 2007).

Long-term catch data suggest that chub mackerel were replaced by Japanese sardines and sardines were replaced by anchovies, Pacific saury, jack mackerel, and common squid. However, it seems strange that the catch of chub mackerel unexpectedly increased in the TWC region in the 1990s, while remaining low in the KOC region (Fig. 6e). The high catch area of the Korean purse seine fishing fleet moved from the Korea Strait in the 1980s to the southern Yellow Sea in the 1990s. The anchovy catch from Korean and Chinese fishing fleets sharply increased in the TWC region in the 1990s (after the climate regime shifts in the late 1980s). It is postulated that the increase in chub mackerel abundance is attributed to favorable environmental conditions (increased food such as anchovy and plankton biomass) and increased recruitment in association with the climate shifts in spite of continuous heavy fishing as seen in the tropicalization in the population structure (e.g. body length and catch rates of immature fish; Fig. 11).

Three elements affecting the total catch are discernible: the abundance of the fish population, its availability to the fishing fleets, and the fishing effort. Distinguishing abundance and availability presents a problem in marine ecology (e.g., biology and oceanography). Availability is a matter of distribution and behavior. For example, the fish population may be as large as usual, but if it does not approach close enough to the fishing grounds in the TWC or KOC region to enter the range of the fishing fleet, the availability will be low. Availability is also affected by accessibility and vulnerability to the fishing gear.

A Hypothesized Mechanism Inducing Climate-Induced Fluctuations in Pelagic Fish Populations in the Far East (KOC and TWC Regions)

Year-to-year changes in abundance of pelagic fish populations (e.g., jack mackerel)

The oceanic conditions in years with strong winter monsoons and their effects of transport of larvae and juveniles enhanced the regional difference in recruitment of fish. For example, the bulk of the jack mackerel catch shifted from the TWC to the KOC region when larval transport to the KOC region was increased by the enhanced winter monsoon in the winter of 1962/1963. The fish that would otherwise have been available in the TWC region were shifted to the KOC region without a time lag because most of the fish taken from the two regions are ≤ 1-year-old fish (Figs. 6d and 11).

Decadal scale climate shifts and regional differences in pelagic fish populations

① Climate shifts: Deep Aleutian Low Pressure (ALPI) covaried with Arctic Oscillation (AOI) and strong Asian winter monsoon (MOI). Strong Subarctic cyclonic circulation → Southward shift in the First Oyashio Intrusion (FOI) → Enhanced Subtropical anticyclonic circulation → Increased Kuroshio volume transport → Increased larval transport to the Kuroshio/Oyashio Current region (KOC) from the East China Sea → Increased recruitment to the KOC region in the 1980s.

② Strong Asian winter monsoon covaried with the deep ALP → Weakened Tsushima Warm Current → Cool regime in the TWC region → Limited larval transport to the TWC region → Low abundance of the pelagic fishes such as jack mackerel, anchovy and chub mackerel in the TWC region in the 1980s (Table 3).

③ Climate shifts: Weakened Aleutian Low Pressure (ALPI) covaried with Arctic Oscillation (AOI) and weakened Asian Winter Monsoon → Weakened Subarctic cyclonic circulation → Northward shift of First Oyashio Intrusion (FOI) → Warm thermal regime in the Oyashio region → Weaken subtropic anticyclonic circulation → Decreased Kuroshio volume transport → Limited larval transport from the East China Sea to the KOC region → Decreased recruitment of pelagic fishes after the climate regime shifts (1987/88) and in the 1990s.

④ Weakened Asian winter monsoon covaried with the weak ALP → Strengthened Tsushima Warm Current → Warm regime in the East China Sea → Northward shift of the spawning grounds → Increased larval transport to the TWC region → High rates of recruitment to the TWC region → Increased in abundance of warm water origin pelagic fish populations in the TWC region.

The recruitment of Japanese sardines sharply decreased in 1988 in association with the climate regime shift in 1988/1989, and the pelagic fish populations of warm/ temperate water origin (e.g., jack mackerel, anchovy, Pacific saury and common squid) sharply increased. Their abundance remained high during the warm regime associated with the mild winter monsoon in the 1990s.

After the regime shift in 1988/1989 (and persisting in the 1990s), a weak (negative) MOI co-occurred with the weak (negative) ALP, and hence all the signs were reversed, resulting in increased abundance of fish populations in the TWC region and decreased abundance of fish populations in the KOC region in the 1990s.

CONCLUSION

The year-to-year regional differences in the pelagic fish populations can be explained on the basis of different recruitment rates in relation to the winter monsoon-induced transport of larvae and juveniles from the main source area in the East China Sea. We presented a hypothetical mechanism for climatic induction of the regional oscillation based on oceanic conditions and zonal differences in recruitment of fish populations between the two (KOC and TWC) regions. In our model, the increased rates of fish larval transport to the Pacific side (KOC region) from the spawning grounds during the increased Kuroshio volume transport in the southern East China Sea associated with strong Asian winter monsoons co-occurring with the deep Aleutian Low Pressure resulted in increased recruitment and abundance of pelagic fish in the KOC region in the 1980s. Subsequently, the warm regime in the Tsushima Warm Current region during the weak Asian winter monsoon and the weak Aleutian Low Pressure were responsible for the increased recruitment and abundance of warm-water-origin fish (e.g., jack mackerel, chub mackerel, anchovy, and common squid) in the TWC region in the 1990s.

The duration of the periods of abundance for jack mackerel and chub mackerel seems to be partly controlled by the tropicalization of the fish under the heavy fishing but the long-term fluctuations in abundance of the fishes are attributed to the ocean climate shifts. The unusually high abundance of chub mackerel in the TWC region in the early 1990s suggests that they are out of phase in the species alternation cycle. The population structure and abundance of the Pacific saury were sensitive to the short-term and decadal scale climate regime shifts, suggesting that the fish can be used as a bio-indicator for the marine ecosystem changes. Japanese sardine populations in the Far East increased in the density-independent (environment-dependent) growth form in the 1970s when warm water prevailed in the spawning grounds and cold and productive waters expanded in the feeding grounds in the north. The density dependent growth form in the sardine population was identified in the KOC and TWC regions in the second abundant period in the 1980s. However, the short generation time (3~4 years) compared with the duration of the period of dominance (10~15 years) indicates the importance of the environment-dependent growth form for long-term abundance fluctuations. The similar patterns of abundance fluctuations in association with ocean climate changes and changes in the growth form of the Japanese sardine in the two regions suggest that they comprise a single large population with its source area in the East China Sea and its adjacent regions.

We suggest that there is possibility of homogeneity in the structure of the pelagic fish populations (e.g., jack mackerel, Pacific saury, common squid) in their entire population ranges in the Far East on the basis of regional oscillations in recruitment and possible mixing between the local groups and stocklets. Larger scale international research will be required to test our hypothesis about the mechanism by which climate-induced ocean conditions drive zonal oscillations in the regional differences in the recruitment of pelagic fish populations.

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