Ocean Science Journal, Vol. 42 No. 3, 179-192(2007)

Review

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Climate Variability and Its Effects on Major Fisheries in Korea

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Received 14 August 2007; Revised 12 September 2007; Accepted 19 September 2007

Abstract – Understanding in climate effects on marine ecosystem is essential to utilize, predict, and conserve marine living resources in the 21st century. In this review paper, we summarized the past history and current status of Korean fisheries as well as the changes in climate and oceanographic phenomena since the 1960s. Ocean ecosystems in Korean waters can be divided into three, based on the marine commercial fish catches; the demersal ecosystem in the Yellow Sea and the East China Sea, the pelagic ecosystem in the Tsushima Warm Current from the East China Sea to the East/Japan Sea, and the demersal ecosystem in the northern part of the East/Japan Sea. Through the interdisciplinary retrospective analysis using available fisheries, oceanographic, and meteorological information in three important fish communities, the trend patterns in major commercial catches and the relationship between climate/environmental variability and responses of fish populations were identified. Much evidence revealed that marine ecosystems, including the fish community in Korean waters, has been seriously affected by oceanographic changes, and each species has responded differently. In general, species diversity is lessening, and mean trophic level of each ecosystem has decreased during the last 3~4 decades. Future changes in fisheries due to global warming are also considered for major fisheries and aquaculture in Korean waters.

Key words – climate change, marine ecosystem, fisheries, Korean waters

1. Introduction

Fisheries resources have fluctuated historically, and evidence in many cases has indicated that corruption of fish species was from overfishing. On the other hand, due to the recent increase in greenhouse gases in the atmosphere, the world's climate is rapidly changing; in turn, the earth/ocean ecosystems are responding to these climate changes. The air-sea interaction, which is closely connected to the large-scale environmental changes, is the main driving force in controlling the climate and the fluctuation of marine organisms. It has been noticed that the oceanic productivity is not stable under these changing environments. Comparing the current ecosystem to the past, it was found that the present conditions of the ecosystem, including fishery resources, have been modified seriously. Abundance and distribution of the species as well as species composition and carrying capacity of ecosystems vary from one climate regime to another. For example, the shape of the ecosystem in the North Pacific was altered significantly during the 1970s' climate regime shift period (Brodeur and Ware 1992; Francis and Hare 1994). Consequently, the biomass of fishery resources, which usually occupy the upper trophic level in marine ecosystems, has been inevitably changed from year to year because their growth and survival depends on the availability of food organisms which are sensitive to environmental conditions. Up to this date, the separation of anthropogenic and natural causes on fishery yields has not been easy to solve.

Fish populations have been adapting to oceanic phenomena over evolutionary time scales, so that their survival rate should be high during an ordinary period. The episodic changes in climate/environments, however, result in changes in a population's survival, and in changes in productivity and species composition. Recruitment failure of fish populations caused by high mortality during the early life stages is detrimental in maintaining

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healthy stock conditions. Most hypotheses on recruitment processes are closely related to the plankton-based ecosystem, which largely depends upon oceanic variability (Cole and McGlade 1998). In order to delineate the effect of ecological interaction among fisheries resources, time-series data on production of fisheries resources and observation on the environment are required. The new paradigm of ecosystem response to environmental variability has become the main theme in marine ecology and fishery science. This type of research provides the understanding of cause and effect mechanisms, as well as prediction capabilities for fisheries recruitment related to climate changes. These in turn could eventually be used to establish appropriate fisheries resource management procedures (Kim *et al*. 2006; Kim and Lo 2001).

The Korean Peninsula is surrounded by the Yellow Sea to the west, the East China Sea to the south, and the East/Japan Sea (which also is called the Japan/East Sea, the East Sea, the Sea of Japan, or the Japan Sea) to the east. In Korean marine waters, fishermen commercially utilize more than one hundred. Fisheries in South Korea yield over 1 million metric tons (MT) of marine fish from Korean waters annually. In general, the increase in fishing activities since the 1970s has reduced fish populations in Korean waters. FAO records indicate that total catches of fish and invertebrates from 1960 to 2005 averaged 1,143,478 MT. The largest catch of 1,725,820 MT occurred in 1986 (Fig. 1). Catches were relatively stable from 1981 to 1996, over 1.4 million MT, except the two years of 1991-1992, and have decreased slightly in recent years. Although it is not clear how major climatic events influenced ecosystems and fisheries resources in Korean waters, some retrospective analyses with historic data sets

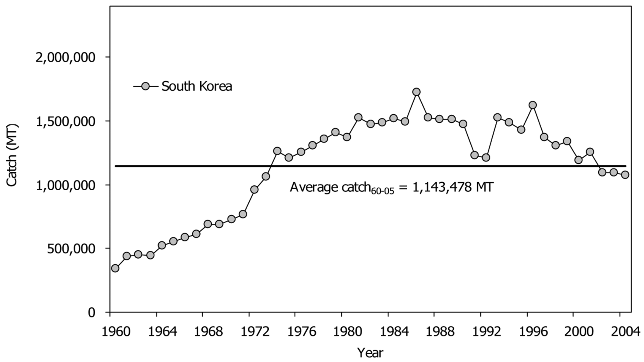

Fig. 1. Total catches of fish and invertebrates in Korean waters since 1960. FAO: http://www.fao.org/fi/statist/FISOFT/FISHPLUS.asp#Download.

have shown correlative relationships between abiotic and biotic components (Kang *et al*. 2000; Kim and Kang 2000; Kim *et al*. 1997; Seo *et al*. 2006; Zhang and Gong 2005; Zhang and Lee 2001; Zhang *et al*. 2000; Zhang *et al*. 2004). In this paper, the current status of Korean fisheries and environmental variability is reviewed. Some effects of climatic events such as global warming, atmospheric circulation patterns, climate regime shifts in the North Pacific, and El Niño events in the tropical Pacific on Korean marine ecosystems and fisheries are summarized, and the impact of future climate change on fish resources for the major target species are discussed.

2. Climate and Marine Ecosystems

Climate parameters such as air temperature and precipitation, often expressed or reflected by indices, have significant impacts on the ocean, and changes in ocean environment reconstruct its ecosystem. Pan-Pacific climate events would influence physical properties of seawater and biological phenomena in the entire north Pacific. The most significant indices in the Pacific are Pacific Decadal Oscillation (PDO) Index, Aleutian Low Pressure (ALP) Index, Southern Oscillation Index (SOI), and Arctic Oscillation (AO) Index. Those indices were developed from different spatial coverage, and indicate different characteristics in periodicity. In the northeastern Pacific, there were two climate regime shifts in 1976/77 and 1988/89. The PDO index, which is the first component from EOF analysis using monthly SST anomalies in the North Pacific, shows such interdecadal climate fluctuation over the north Pacific (Mantua *et al*. 1997). In Korean waters, some direct or indirect indications of changes were found around the late 1970s and late 1980s. Details of variability and relationships between indices are well described in Chang *et al*. (in press) and Otterson *et al*. (in press).

The Korean Peninsula is located in monsoon areas of the mid latitude where the Siberian High and the subtropical Pacific Low collide producing cold-dry winters and warm-wet summers. North and northwest winds in the autumn and winter are strong, and wind speeds easily reach 10 m s^{-1}. Winds reverse direction and become weaker in the spring and summer. Typhoons developed in the west subtropical Pacific bring heavy rains in the summer and autumn, and about nine typhoons pass through the Korean Peninsula

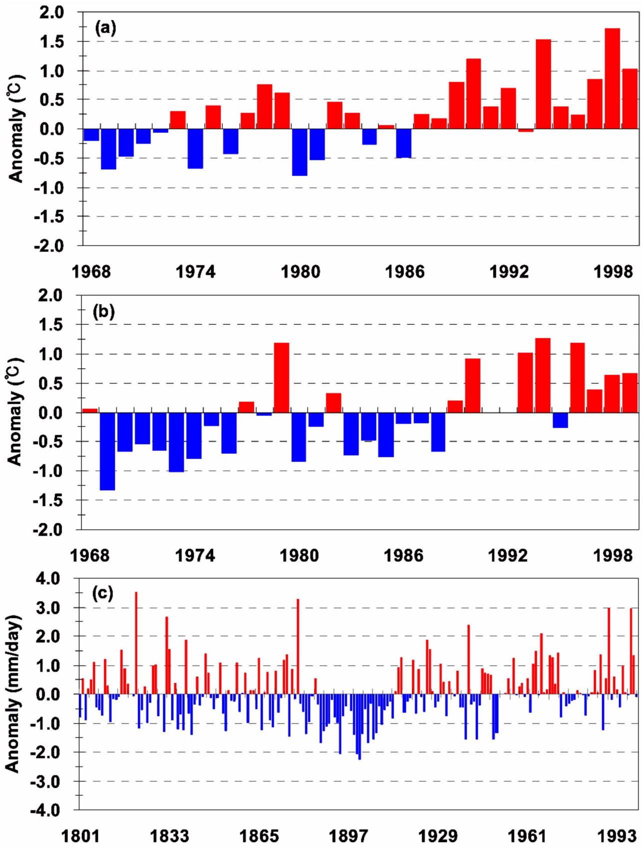

Fig. 2. Time-series of (a) mean air temperature anomaly over the Korean Peninsula, (b) change in seawater temperature in December at 50 m off the southern coast, and (c) precipitation in Seoul.

every year (Kim and Khang 2000). The increasing trend in air temperature over the Korean Peninsula is obvious. The rate of increase was estimated as 0.23 °C/decade over the Korean Peninsula since the 1960s (Fig. 2a). Aside from the long-term trend of warming, there was an alternate pattern of mean seawater temperature. In the surface layer off the southern coast, cold water masses were prevalent during the early 1970s through late 1980s, and warm ones since 1989 (Fig. 2b). This phenomenon was typical in the spring and the autumn. It is also anticipated that the current pattern as well as subarctic front systems could be reformed due to climate variability in the East/Japan Sea. Park and Oh (2000) reported that the SST change over Korean waters also seemed to be connected to the El Niño/Southern Oscillation with phase lags of 5 to 9 months, which meant that a cold summer might occur in the East/Japan Sea after an El Niño winter. Kim and Kang (2000) also showed a significant relationship between SOI and December SST in the East China Sea. After the mid-1970s, the frequency of strong storms and heavy rain also increased. The precipitation pattern over the Seoul area indicated that 2-4 year wet and dry periods alternated since the 1800s, except for a long dry period from 1880-1910. Recently, a wet period appeared in Seoul during the mid 1950s through the early 1970s, a dry period from the mid 1970s to the mid 1980s, and a highly wet period after the late 1980s (Fig. 2c). The AO index changed to positive and Asian monsoons weakened after the late 1980s, resulting in high temperatures and enhanced zooplankton biomass in the Tsushima Warm Current (Tian 2006).

Changes in environment in the spring have an especially profound effect on oceanic productivity. Sea surface temperature (SST) is usually influenced by horizontal advection and direct exchange of heat through air-sea interaction. As indicated by Hahn (1994), there has been an increase of around 2 °C in February SST in Korean waters during the past one hundred years. The increase in August water temperature was about 1.0 °C. The rate of change has increased during the past decade. Hahn (1994) also showed a northward movement of isotherms during the same period.

In the East/Japan Sea ecosystem, some differences in ecosystem structure and productivity have been observed during the 1960s through 1990s. Mixed Layer Depth (MLD) increased after 1977 and fluctuated around depths of about 40 % deeper than prior to 1976 (Zhang *et al.* 2000). The mean transparency depth from Secchi disk observations was 11.9 m during the 1960-1975 period, but increased to 14.2 m during the 1976-1990 period. This result implied higher primary productivity (and consequently the zooplankton biomass) during the earlier period (Kang *et al.* 2000). Correlation studies indicated that some fish populations (saury and sandfish) catches occurred when the SOI was positive (*i.e.* La Niña period), when spring chlorophyll was high, when air temperatures were cooler in coastal cities, and when catches of sardine and walleye pollock were low (Fig. 3; PICES 2004). Chiba *et al.* (2005) argued that the planktonic community in the surface layer reflected regime shifts in 1976/77 and 1988/89. It was also found that the rapid growth of pine trees in coastal areas appeared after a protracted El Niño event (Kang *et al.* 2000).

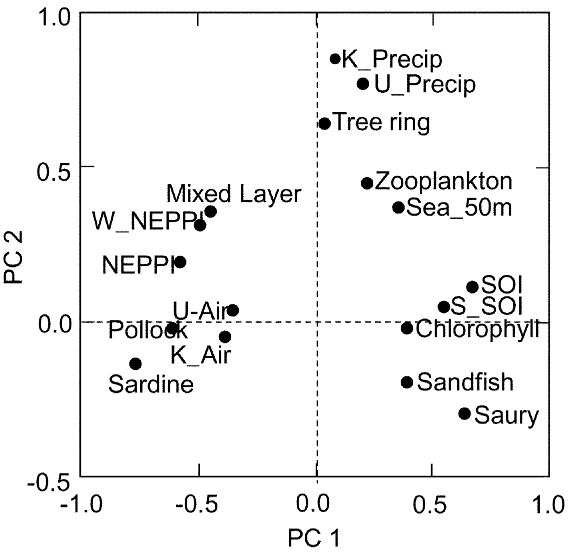

Fig. 3. Principal component ordination of correlations between fish catches and environmental variables in Korean waters from 1960-1990. NEPPI (annual North East Pacific atmospheric pressure index), W_NEPPI (winter only), SOI (annual Southern Oscillation Index), S_SOI (spring only), U_Precip, U_Air, K_Precip and K_Air (spring precipitation and air temperature at Ulleung Island and Kangrung, respectively), and catches of different fish species (PICES 2004).

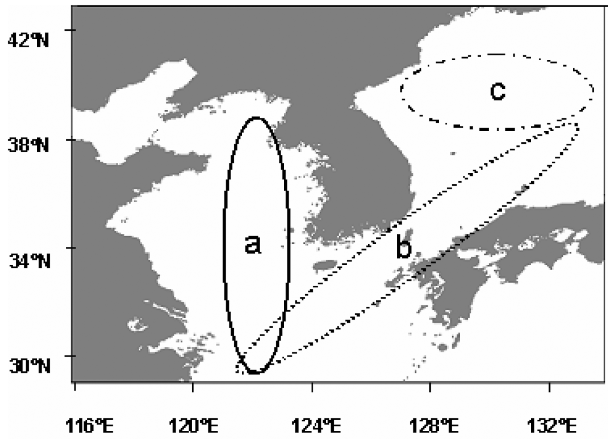

Fig. 4. Three categories of fish communities in Korean waters. (a) Demersal ecosystem in the Yellow Sea and the East China Sea: small yellow croaker, hairtail, etc., (b) Pelagic ecosystem in the East China Sea through the East/Japan Sea: chub mackerel, common squid, etc., and (c) Demersal ecosystem in the East/Japan Sea: walleye pollock, Pacific cod, etc. (Kim 2003).

3. Changes in Fish Communities in Korean Waters

Some resident fish species are found near the coast, while others show a long migration behavior during their life stages. Kim (2003) identified three important ecosystems in Korean waters based on the marine commercial fish catches (Fig. 4): the demersal ecosystem in the Yellow Sea and the East China Sea, the pelagic ecosystem in the Tsushima Warm Current (*i.e.* a branch of Kuroshio) from the East China Sea to the East/Japan Sea, and the demersal ecosystem in the northern part of the East/Japan Sea. Actually, strictly speaking, there is no true demersal population due to the shallow topography of the Yellow Sea. In contrast to pelagic fish species (*e.g.* anchovy), small yellow croaker and hairtail are found in relatively deep waters in the center of the southern Yellow Sea, so we regarded this species as demersal fish. It is worthy to note that Pacific cod and herring populations used to be abundant in the cold water mass of the deep trough area in the central Yellow Sea, but overfishing within the confined fishing grounds resulted in the depletion of these stocks.

Most species in these three regions are migratory. Fishes in the Yellow Sea and the East China Sea spawn in coastal areas during the spring, feed to the north during the summer, and overwinter after southward movement to the East China Sea. The demersal species in the East/Japan Sea seem to have an onshore-offshore or south-north migration seasonally. In addition to these ecosystems, surface layers of the Yellow Sea and the northern part of the East/Japan Sea are important habitats for anchovy and fingerling chum salmon, respectively. Such migratory behavior of species is likely a big contribution in distributing biological energy from one area to another in the northwestern Pacific Ocean (Kim 2003).

In general, the increase in fishing activities since the 1970s has depressed fish populations in Korean waters, and higher fishing effort is required to achieve catches comparable to those of the past. Walleye pollock, small yellow croaker, hairtail, anchovy, sardine, chub mackerel, Jack mackerel, filefish, saury, and common squid are the major fisheries in Korea. These are the key species in the catch, accounting for about 60 % of the total catch since 1980 (Table 1). Most commercial fisheries resources in Korean waters seem to be overexploited because neighboring nations share these resources without proper management regulation. Due to the high fishing activities in the region since the 1970s, annual catches increased or were stable in the 1980s and 1990s, but catch per unit effort (CPUE) decreased dramatically and trophic levels have sharply

Table 1. Mean annual catches (MT) of major species in the fisheries of South Korea during the last three decades. Small pelagic fishes are indicated by an asterisk (*).

	1975-1979	1980-1984	1985-1989	1990-1994	1995-1999	2000-2004
Anchovy* (*Engraulis japonica*)	159,449	160,649	154,170	189,847	237,334	231,637
Chub mackerel* (*Scomber japonicus*)	102,072	98,963	119,954	138,063	225,279	159,539
Walleye pollock (*Theragra chalcogramma*)	91,001	118,493	47,619	17,774	6,468	299
Hairtail (*Trichiurus lepturus*)	94,891	137,533	111,059	89,207	75,102	70,054
Filefish* (*Navodon modestus*)	150,876	190,590	223,693	70,265	6,442	1,620
Small yellow croaker (*Pseudosciaena polyactis*)	34,301	23,899	14,726	34,620	19,667	12,635
Sardine* (*Sardinops melanosticta*)	33,203	100,199	158,253	58,392	13,175	515
Jack mackerel* (*Trachurus japonicus*)	5,949	7,163	19,870	27,576	17,052	21,810
Saury* (*Cololabis saira*)	26,035	7,442	4,568	2,525	10,173	7,340
Common squid* (*Todarodes pacificus*)	29,031	45,205	51,287	146,805	218,296	224,919
Mean annual catch of 10 major species	726,809	890,136	905,199	775,073	828,990	730,369
Mean annual catch of 7 small pelagic fish/ the proportion (%) to the total in parenthesis	506,615 (38.7)	610,211 (41.4)	731,795 (47.1)	633,472 (44.3)	727,752 (51.5)	647,381 (56.7)
Mean annual total Korean catch	1,308,374	1,475,485	1,553,815	1,431,964	1,412,168	1,142,025

decreased in the catches from marine ecosystems of Korea (Zhang and Lee 2004). Moreover, current fishery yields by Korean fishermen are composed mostly of immature fish. The decrease of CPUE and higher portion of immature fish are evidence of overfishing. In these circumstances, the current fishery cannot be sustainable on a long-term basis.

In addition to the reduction of stock biomass, changes of species composition and trophic level of the overall fish community are obvious. Demersal fish used to predominate on the Korean side of the Yellow Sea and the East China Sea in the 1960s (Zhang and Kim 1999): demersal fish (66 %), pelagic fish (18 %), cephalopods (7 %), and crustaceans (7 %). Bottom trawl surveys in the Korean side of the Yellow Sea also show a change in abundance and diversity of demersal species between the 1960s and 1980s. One hundred thirty-four demersal fishes were collected in the summer of 1967, while only 51 demersal species were collected in the 1980/81 survey, revealing a 62 % reduction in the number of species. Moreover, a shift in the major species was found. Among the top 15 most abundant species in the 1980/81 survey, 8 species were not found in the list of the 20 most abundant species in the 1967 survey (Zhang and Kim 1999). Tong and Tang (2002) reported that demersal species were dominant in the Chinese side of the Yellow Sea in 1959, but small pelagic fish and invertebrates dominated there about 20~30 years later.

Commercial catches in the East/Japan Sea also indicated remarkable changes in species composition (Fig. 5). The ecological regime shift between small pelagic fish and demersal fish was especially evident. In the 1960s, common squid catch occupied 43 % of the catch in the East/Japan Sea, followed by saury (15 %) and walleye pollock (12 %) (Zhang *et al*. 2004). Walleye pollock increased, constituting about 33 % of the catch in the 1970s and the 1980s, and concurrently, the proportions of common squid greatly decreased. The dominant fisheries catch also shifted from saury, cod, and pollock in the 1980s, to common squid in the 1990s occupying about 45 %. The abundance of small pelagic fish and invertebrates has increased in the Tsushima Warm Current ecosystem. In recent years, seven major small pelagic species in Table 1 occupied around 57 % of the total catch, and common squid alone around 20 %.

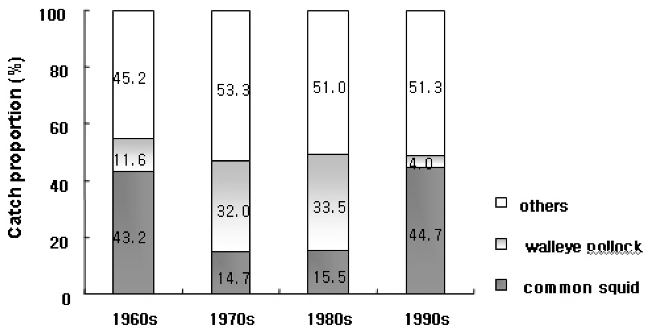

Fig. 5. Catch proportions of East/Japan Sea by species (1961-2000) (modified from Zhang *et al*. (2004)).

Recent statistics indicate that cold-water species such as

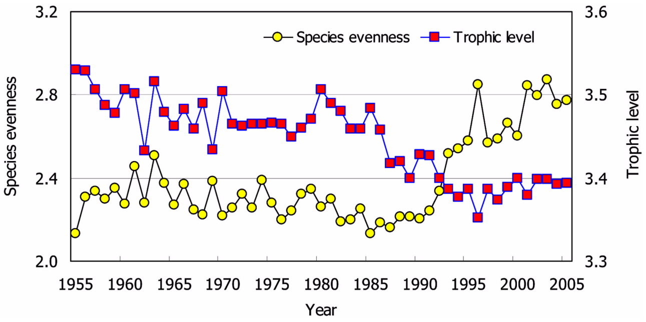

Fig. 6. Trophic level and species evenness of fisheries resources in Korean waters.

Pacific cod and herring in the Yellow Sea are nearly extinct or have greatly decreased due to the warming of the water mass and/or due to the intensive fishing operation in the cold-water mass in the trough area of the central Yellow Sea. Furthermore, the schools of migratory species have been pursued by fishermen from overwintering areas in the East China Sea through spawning and feeding grounds near the coastal areas, so that both recruitment overfishing and growth overfishing (*i.e.* reduction in both recruitment rate and length) have been common for small yellow croaker and hairtail. Although the processes behind such changes are conflated, both unregulated overfishing and environmental change are probably responsible.

The mean trophic levels of resource organisms from the Korean waters showed a decreasing trend during the four decades (Fig. 6). Mean trophic level was about 3.46 until early 1980s, but it decreased rapidly during mid 1980s through early 1990s, and stabilized to about 3.40 after the late 1990s (Zhang and Lee 2004). Demersal higher trophic level fish (*e.g.* small yellow croaker) gradually decreased, and lower trophic pelagic fish (*e.g.* anchovy and common squid) increased. More specifically, the decline in the trophic level for the Yellow Sea fishes was steeper than for the East China Sea fishes. In the East/Japan Sea, however, the mean trophic level increased from 3.09 to 3.28 during the 1976 regime shift period (Zhang *et al.* 2004). The 1988/89 regime shift event changed biomass and production of fisheries resources in the southwestern Japan/East Sea. The total biomass of all groups was increased by 59 % after this regime shift. The relative contribution of walleye pollock, at trophic level 3, to the total flow of energy decreased drastically from 33.0 % to 4.3 %, while that of common squid, at the same trophic level, doubled from 34.2 % to 72.2 % during the periods (Zhang *et al.* 2007). Increase in the evenness of fish species from the Korean commercial fishery production was followed, after decrease in the mean trophic level of fisheries resources ($r=-0.653$, $P<0.01$), with species replacement from demersal to pelagics from the early 1990s. Three major small pelagic species, i.e. chub mackerel, anchovy, and common squid, occupied about 55% of total commercial catches, which was averaged to be about 650 thousand MT for the three recent years, 2003-2005.

4. Climate Impact on Fish Populations

Environment components are always changing with time, while fish populations have their own, routine life history or schedule in the ocean ecosystem. Fish spawning is influenced by abiotic environments such as temperature and salinity, and their growth and survival are also controlled by the abundance of prey and predators. Water properties are influenced by climate variability, especially in the coastal zone where spawning and nursery grounds of marine fish species are usually found. Therefore the degradation of the coastal habitats and, consequently, the survival of some migratory species could be threatened by climate changes. An inter-disciplinary approach is essential to elucidate ecological interactions. Marine ecosystems in Korean waters are influenced by many factors such as the Kuroshio Current, seasonal monsoon and wind, river runoff, and the interaction of fish species. Due to the shortage of scientific evidence and data in Korean waters, we are limited in our ability to understand the relationship between climate change and marine ecosystems. Below is a brief description of the environmental impacts on some representative fish populations in each ecosystem around the Korean Peninsula.

Demersal ecosystem in the East/Japan Sea

Walleye pollock are a cold-water and demersal species, and their spawning grounds in Korea are at the southern limit of their distribution. The majority of the walleye pollock population resides in North Korean waters. Annual catches in the Republic of Korea (*i.e.* South Korea) increased from the early 1970s and peaked in 1981 at 0.17 million MT. Since then, catches have declined continuously. The fishing area in the 1990s was restricted to coastal areas in the north, apparently because of the higher SST of the East/Japan Sea. This contrasts to

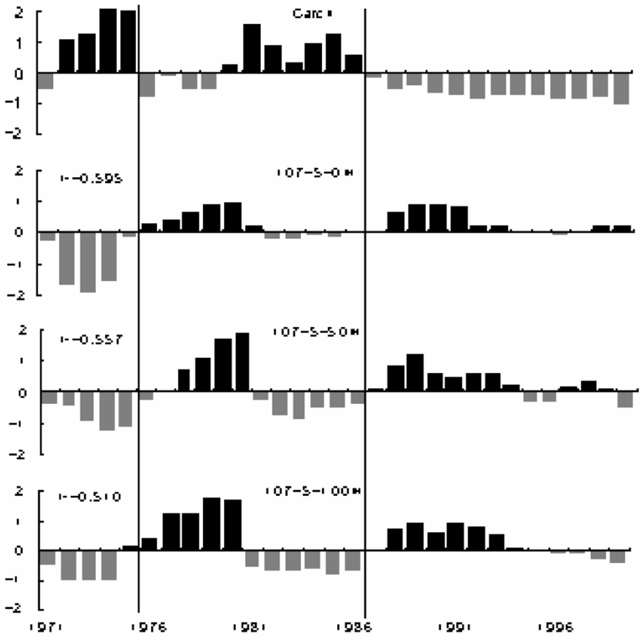

Fig. 7. The relationship between walleye pollock catch and seawater temperature (0-100 m) anomalies off the east coast of the Korean Peninsula. Seawater temperatures used were collected from the KODC's oceanographic observation line, 107-5.

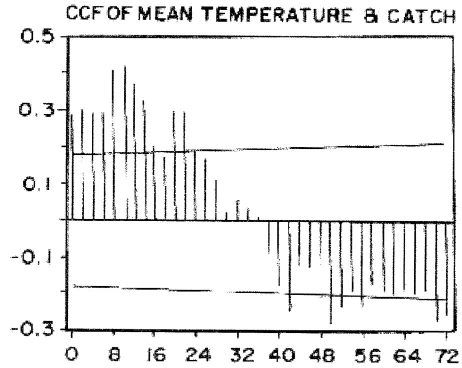

Fig. 8. Cross-correlation coefficient between seasonal anomalies of small yellow croaker catch and seawater temperature at 75 m (Kim *et al*. 1997).

a broader fishing area in the late 1970s when SSTs were cooler. There is a negative correlation between fish catch and local seawater temperatures at a major fishing area off the east coast of the Korean Peninsula (Fig. 7). Negative anomalies in seawater temperature (0~100 m) during the early 1970s and early 1980s were coincident with a positive anomaly of walleye pollock catch, while warm water masses in the late 1970s and after the 1990s resulted in low walleye pollock catches. A shift in fishing season was also noticed in the 2000s. The highest catches were recorded in January-March during the 2000s, compared to November-December during the 1980s. Kang *et al.* (2000) also found that walleye pollock catch is significantly related to the Northeastern Pacific Pressure Index (Fig. 3).

Demersal ecosystem in the Yellow Sea and the East China Sea

Small yellow croakers migrate out to the East China Sea in the winter and return to the Yellow Sea to spawn in the spring. The recruitment success of this demersal species seems to be related to seawater temperature in the deep layer, though spawning happens near the coastal areas. Yields of small yellow croaker and the residual of standard deviation of seawater temperatures appeared to be related (Kim *et al*. 1997). The correlation between the seasonal anomaly of mean temperature at 75 m depth and the seasonal anomaly of fish catch was highly positive and significant with a time lag of 8-14 months (Fig. 8): the warm spawning period and homogeneous temperature condition of the previous year caused the increase in the following year's yield of this species. This phenomenon also reflects that the year class strength of small yellow croaker might be determined by oceanographic conditions of fish habitats where either mature adults or very young fish live, since the catches of small yellow croaker are made up primarily of fish younger than age two.

Hairtail are distributed in the southwestern waters off Jeju Island during the period of January-March. The main group migrates northward along the west coast of the Korean Peninsula and reaches the central parts of the Yellow Sea in July and August. Spawning occurs between June and October with peak spawning in August. The return migration southward begins in September, and reaches the wintering area off Jeju Island by November. When the bottom water of western Jeju Island in the summer was above 14.0 °C, the catch was large. In contrast, the catch was poor when the temperature of that water was below 13.0 °C. Therefore, the seawater temperature of the bottom layer can be used as an index for forecasting the catch of hairtail (Kim and Rho 1998).

Pelagic ecosystem in Tsushima Warm Current system

Many pelagic fish species reside in the Tsushima Warm Current system, but the catch of each species varies with time. Two patterns of fish catches have characterized the

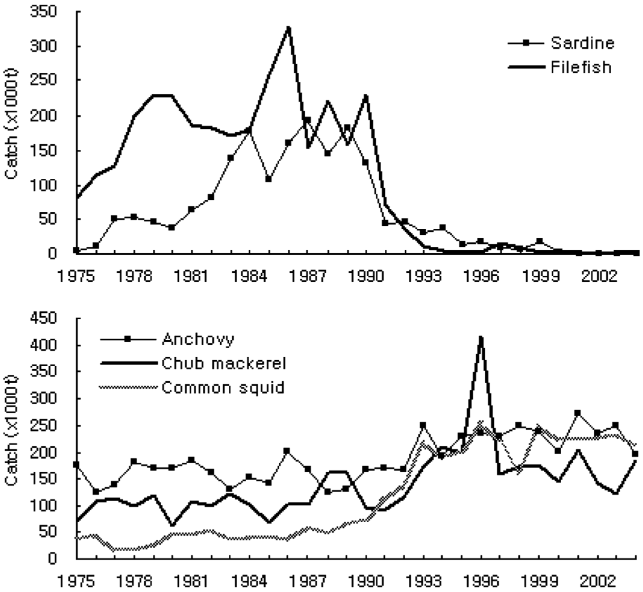

Fig. 9. Two types of catch pattern for small pelagic fish in the Tsushima Warm Current ecosystem during the last three decades.

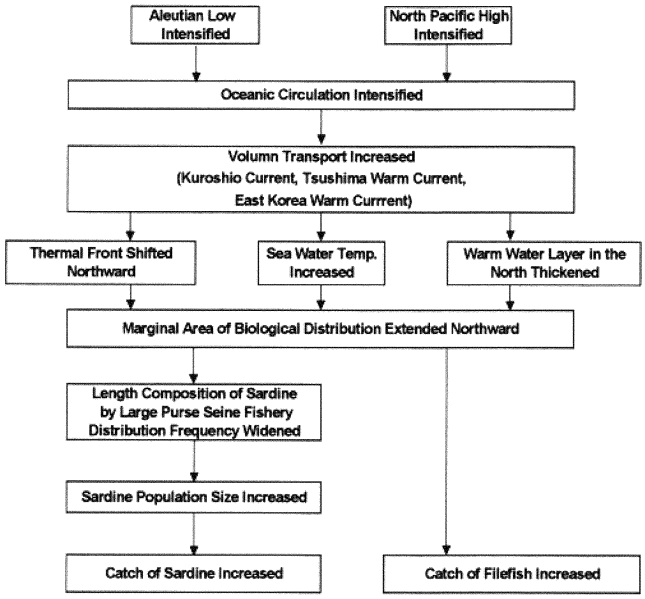

Fig. 10. Diagram showing the effects of the 1976 climate-driven regime shift on filefish population in Korean waters (Zhang *et al*. 2000).

last three decades (Fig. 9): sporadic increase/decrease and continuous increase with time. Sardine and filefish were not abundant before the early 1970s, but were very abundant in the 1980s, then decreased in the early 1990s. On the other hand, the catches of chub mackerel, anchovy, and common squid showed an increasing pattern since the 1970s. Chub mackerel and common squid increases were particularly abrupt in the early 1990s, and stable throughout the 1990s. Most species share the same spawning and nursery grounds, but peak spawning periods are separated to avoid competition for food.

Filefish occupy a relatively broad range of habitats both horizontally and vertically. They migrate and spawn in the East/Japan Sea and the Yellow Sea within the warm current from April or May. Some schools reach the North Korean coastal areas and spend the summer there. Another group then migrates to the Yellow Sea, occupies the whole Yellow Sea in June, and migrates south in October. The production of filefish increased after the late 1970s, and the fishery collapsed in the early 1990s due in part to overfishing (Fig. 9). The increased volume transport of the Kuroshio Current and MLD in the East/Japan Sea during 1976-77 might be responsible for such an increase in catch (Fig. 10).

Sardine spawn off the southern coast of the Korean Peninsula and the western and northern coast of Kyushu from December through June with a peak in February-April. They migrate north in the summer to feed near 45°N, along the east coast of the Korean Peninsula. In November, they move the southern coast of the Korean Peninsula. Variability in the Kuroshio current, which is related to the transport processes for sardine eggs and larvae in Japanese waters, plays a critical role in the fluctuation of sardine populations (Yatsu *et al*. 2005); this in addition to the effect of exploitation. In Korean waters, the abundance and geographical coverage of sardine eggs/larvae were high in the 1980s when spawning biomass was high, and vice versa in the 1970s and the 1990s (Kim *et al.* 2006). Decadal-scale changes in seawater temperature at 50 m during the spring indicated cool temperatures during the early to mid 1980s followed by warm waters since the late 1980s. Also, feeding and spawning areas based on fisheries information exhibited the same pattern of extension/contraction as seen in ichthyoplankton surveys, as it was shown in MacCall (1979). The sardine catch had a high positive correlation with chlorophyll-a concentration in April, and negative correlations with chaetognaths in April and euphausiids in June (Table 2).

Sardine populations also seem to be influenced by the regime change that occurred at the late 1970s and late 1980s. Catches were very high between these two events.

Table 2. Selected correlation coefficients, which were statistically significant for fish catch *vs* their biotic and abiotic environmental factors. Sampling month in parenthesis; * indicates that the correlation is significant at the 0.05 level, and ** at the 0.01 level (Kim and Kang 2000).

Variable	Anchovy	Chub mackerel	Sardine
Anchovy	1.0	0.790**	0.453*
Chub mackerel	0.790**	1.0	0.602**
Sardine	0.453*	0.602**	1.0
SST (Dec.)	0.419*	0.436*	0.327
Chl. a (Apr.)	0.186	0.019	0.561**
Chl. a (Jun.)	0.635**	0.523**	0.264
Chl. a (Aug.)	0.442*	0.377	0.276
Zooplankton (Feb.)	-0.559**	-0.406*	-0.339
Zooplankton (Apr.)	-0.304	0.408*	-0.291
Copepods (Apr.)	0.563*	0.434	-0.398
Copepods (Jun.)	0.121	0.571*	-0.042
Copepods (Dec.)	0.635*	0.477	-0.277
Chaetognaths (Apr.)	0.647**	0.307	-0.499*
Chaetognaths (Oct.)	0.728**	0.512*	-0.321
Chaetognaths (Dec.)	0.558*	0.129	-0.427
Euphausiids (Jun.)	0.349	0.356	-0.550*
Euphausiids (Dec.)	0.768**	0.603*	-0.492
Amphipods (Apr.)	0.713**	0.504*	-0.395
Amphipods (Dec.)	0.712**	0.616*	-0.423

The fluctuation pattern of sardine catches in Korean waters generally coincided with that of Japanese sardine, although the Kuroshio Current off Japanese islands has no direct link to Korean populations. Zhang *et al*. (2000) hypothesized that the increased volume transport of Kuroshio in the East China Sea resulted in high catches of filefish and sardine due to the strong influx of the warm Tsushima Current into the Korean Strait and the East/Japan Sea (Fig. 10). Intensity of the Kuroshio Current has increased since 1976. As a result, the intensity and frequency of spring blooms decreased in the East/Japan Sea and the intensity of autumn blooms increased. Sardines are resident in the East/Japan Sea from June to November; therefore it was speculated that an autumn bloom was more advantageous to them than was a spring bloom. This could account for the dramatic increase in the sardine stock after 1976 (Zhang *et al.* 2000). However, there is no clear understanding of historic fluctuations in the sardine population of the northwestern Pacific.

Anchovy occur primarily in the Korea Strait and the southern Yellow Sea during winter, and migrate shoreward to the southern coast of Korea to spawn in April-August. In many ecosystems around the world, abundance of anchovy and sardine alternate in time (Lluch-Belda *et al*. 1989, 1992). In Korean waters, however, this did not occur. Figure 9 shows that the anchovy catch has increased continuously, even though sardine catches were high in 1980s. Elevated seawater temperatures in December showed a positive correlation with El Niño, and seemed to cause high growth for anchovy, and strong year-class for those populations in Korean waters (Kim and Kang 2000). Statistically, the seasonal and long-term trends of embryonic mortality, egg production and spawning stock biomass of anchovy can be explained largely by spring warming, summer cooling and by less abundant zooplankton in the late 1980s (Kim and Lo 2001). A matrix of simple correlation coefficients among planktonic organisms and fish indicated that the anchovy catch had a high correlation with chlorophyll-a concentrations in June and August, and had high correlation coefficients with large zooplankton such as chaetognaths, euphausiids, and amphipods in fall and winter (Kim and Kang 2000; Table 2). Small pelagic fishes have been known to be the main food item for the higher trophic level fishes such as Spanish mackerel, hairtail and so on (Huh 1999). Decreasing higher trophic level fishes may influence the density of small pelagic fishes through the change of prey-predator relationship.

Chub mackerel are widely distributed in the coastal areas of the northwestern Pacific. The Korean stock of this species stays in the northeastern East China Sea during December-February, and spawns between Jeju Island and Tsushima Island in Korean waters from April to June (Hwang and Lee 2005). The 1988 climatic regime shift affected the habitat of chub mackerel by widening and moving it to the west of 128°E, and the distributional overlap of chub mackerel and Jack mackerel decreased after 1988 (Zhang *et al*. 2004). Mean length of chub mackerel in fishery tended to decrease after the 1970s, and the portion of small mackerel increased: the fork length in commercial catch was about 32 cm in the early 1970s, but decreased continuously, and the mean fork length in 2002 was 29.2 cm. Recruitment was found to be correlated with salinity ($r=0.454$, $P<0.05$), zooplankton biomass ($r=0.692$, $P<0.01$), and copepod biomass ($r=0.815$, $P<0.01$) (Choi *et al*. 2000). Chub mackerel catches were also significantly correlated with SST in December, chlorophyll-a in June, and large zooplankton in the fall

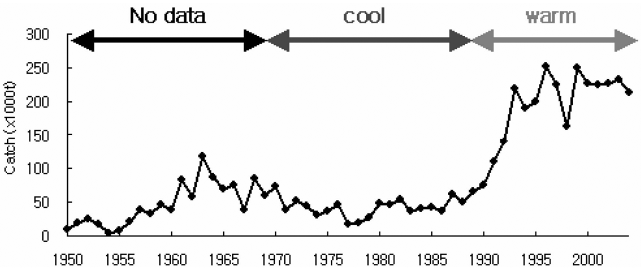

Fig. 11. Total catch of common squid (*Todarodes pacificus*) in Korean waters. Alternation of warm and cool water temperatures off the southern coast of the Korean Peninsula during December is indicated by arrows.

and early winter (Table 2).

The life span of common squid in the northwestern Pacific has been assumed to be one year (Nakamura and Sakurai 1993), and their spawning seasons in the East China Sea and the southern East/Japan Sea are spread throughout the year: *i.e.* summer (June-August), autumn (September-November) and winter (January-March) spawning groups. Spawning grounds have not been identified precisely, but it is known that successful spawning locations are selected based on seawater temperature, bottom topography, and pycnocline depth (Sakurai *et al*. 2006). In Korean waters, common squid catches increased abruptly during the early 1990s (Fig. 11), primarily by fisheries in the East/Japan Sea. When the common squid catch increased in the early 1990s, the SST in Korean waters increased concurrently. as shown in Fig. 2c. Seawater temperature near spawning and nursery grounds during winter seemed to be more important than other seasons for controlling stock abundance. Winter temperature off the southern coast was cool during the 1970s and 1980s, but rose in the 1990s, and the winter population of common squid showed a rapid increase compared to the autumn population. A correlation analysis indicated that zooplankton biomass in October and December of the previous year (*i.e.* when common squid were small) showed an extremely significant correlation with common squid catches in September-December in present year. Euphausiids and amphipods are important food organisms for the survival of young common squid in the East/Japan Sea (Kang *et al*. 2002).

Other ecosystems

Chum salmon are cold-water species in the surface layer of the ocean through most of their life. Because of the wide distribution of salmon over the course of their life, environmental conditions at specific areas influence salmon growth, migration route, returning rate, etc. Salmon hatcheries in East/Japan Sea coast are at the southern range of their distribution and would be expected to be negatively affected by a warming of the ocean surface. The homing success of chum salmon might depend on seawater temperature in the coastal areas because high temperatures have resulted in mass mortality of salmon fry when released. The returning rate of chum salmon released from Korean hatcheries is below 1.5 % which is very low compared to American and Japanese chum salmon. There was a negative correlation between return rates and SST during release time in the coastal areas. It has been known that 14 °C is the upper temperature limit for chum salmon fry in coastal areas (Mayama and Ishida 2003), so that high temperatures in the spring of 1988-1990 and 1997-1999 appeared to be detrimental to the survival of released salmon fry, and resulted in the lower return rates of the spawners in the 1991-1994 and 2000-2002 spawning periods, respectively (Fig. 12; Table 3).

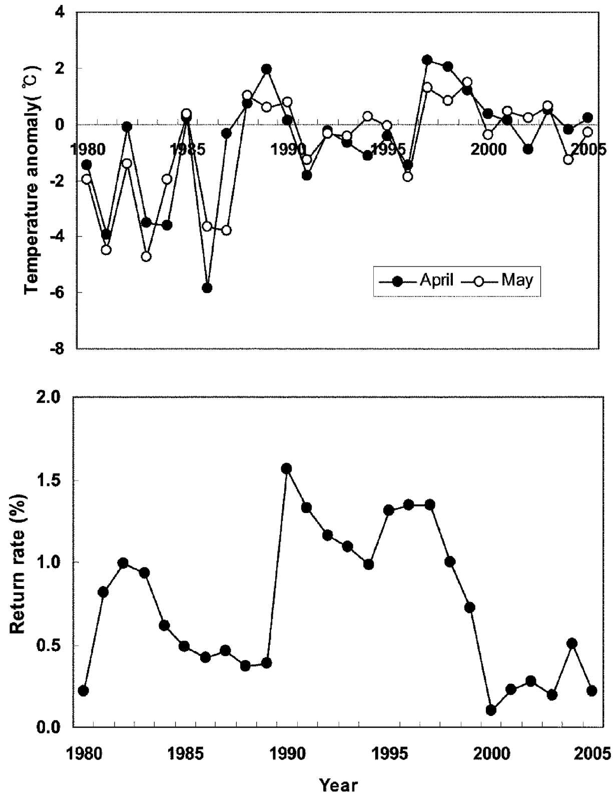

Fig. 12. Seawater temperature anomalies near salmon hatcheries and the return rate of Korean chum salmon. Note that the return rate before 1990 does not include salmon catch in coastal areas of Korea.

Table 3. Means and standard deviations of seawater temperature in eastern coastal area of the Korean Peninsula during Apri and May, 1988~1990 and 1997~1999 periods.

	April	May
1988	11.2 ± 1.0 n = 28	14.7 ± 1.1 n = 30
1989	12.4 ± 0.7 n = 28	14.3 ± 0.9 n = 30
1990	10.6 ± 0.3 n = 27	14.5 ± 2.0 n = 30
1997	12.7 ± 1.0 n = 21	15.0 ± 0.4 n = 25
1998	12.5 ± 1.7 n = 24	14.5 ± 1.8 n = 23
1999	11.7 ± 1.5 n = 24	15.2 ± 1.1 n = 23

Actually, in the coastal areas of the East/Japan Sea, growth rates of fingerling chum salmon were higher in the 1990s than in the 1980s. The increased zooplankton abundance in the East/Japan Sea since the late 1980s might have caused favorable growth conditions for young salmon in the 1990s (Seo *et al*. 2006).

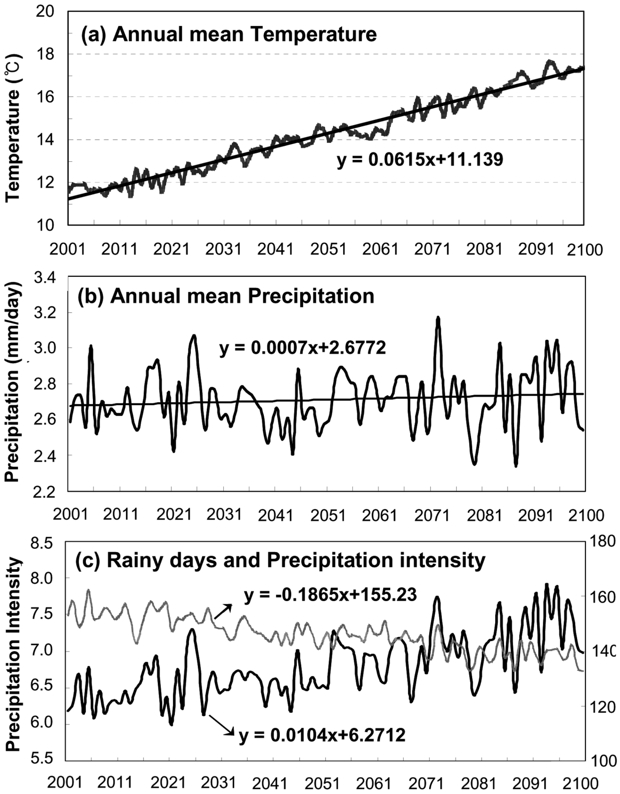

Fig. 13. Changes in climatological parameters, Korean Peninsula and the East Asia for the next 100 years (2001~2100) by the regional climate model based on the SRES A2 greenhouse emission scenario. (a) Annual mean temperature, (b) annual mean precipitation (mm/day), and (c) number of rainy days (light line, right scale) and precipitation intensity (thick line, left scale) over East Asia.

5. Projection of Major Fisheries Due to Climate Change

Projection on abiotic environment

Global warming is evident in Korean waters, and the frequency and the strength of abnormal weather conditions haveincreased recently. Based on the SRES A2 CO_2 emission scenario, future changes in air temperature and precipitation over the East Asia have been forecasted (Fig. 13). The warming rate of annual mean temperature over the Korean Peninsula and the East Asia is 0.61 °C/decade during 2001-2100, so the warming of 5.5 °C is expected in East Asia by the end of this century (Oh *et al.* submitted). Annual precipitation is expected to increase as much as 0.07 mm/day by 2100, and we could have about 2.6 % more precipitation annually in comparison with current annual precipitation (2.68 mm/day). However, the number of rainy days diminished by 19 days in 2100, illustrating that we may have more precipitation and fewer rainy days. Consequently, precipitation intensity (PI) will increase, and we may have more chance to get heavy rainfall associated with global warming.

As expected from Hahn's (1994) schematic temperature isotherms for the last 100 years, higher SST will appear in the future due to the accumulation of CO_2 in the atmosphere. Modeling predictions indicated a 2~3 °C increase in SST in the North Pacific Ocean within 50 years (Mikolajewicz *et al*. 1990). The climate chart based on SST observations in the northwestern Pacific during the 1960s~1980s period showed that the effect of 3 °C increase is equivalent to 500 km northward movement of isotherms in the Pacific side of Japanese islands (Kim 1995). Furthermore, thermal expansion of sea surface due to warming might cause a different circulation pattern in the northwestern Pacific.

Projection of some fisheries and aquaculture

The components of marine ecosystem including fish populations will be reorganized in accordance with climate/oceanographic changes. However, because different fish species have different life cycles and habitat areas, one large-scale climate change might not show the same common effects for all fish species. If the Aleutian Low intensifies under a global warming scenario, the oceanic circulation is consequently affected: the volume of the Kuroshio Current would be stronger, resulting in stronger plankton blooms in the autumn and favorable conditions for sardine and filefish productions. If the more frequent and intense Aleutian Lows observed in the 1980s occur in the future, periods of high sardine abundance may be more frequent.

However, some other species such as saury and sandfish seem to be more related to ENSO than the ALP (Fig. 3). The period of more frequent and intense El Niño in the mid-1990s appeared to be favorable for saury production. Sporadic events such as high seawater temperature influence survival and recruitment of fish populations, although uncertainty in mechanistic processes between environment and biological phenomena still remains. Predictions for future fish stock conditions do not look feasible given current scientific knowledge on the climate variability and cause-effect relationships among ecosystem components.

In general, the retreat of cold water species and colonization of warm water species will be apparent in Korean waters in the 21st century. Actually, the abundance of small pelagic fish including common squid has been increasing in the Tsushima Warm Current system since the early 1990s when SST increased. Far southern species such as spotted mackerel (*Scomber australasicus*) comprised a higher proportion of the catch of mackerel-like pelagic species than before, and the winter catch of yellowtail (*Seriola quinqueradiata*) increased remarkably in the early 1990s when there were higher air temperatures, weak wind speeds, and warmer seawater at 50 m off the southern coast of the Korean Peninsula (Lee and Go 2006). If wind intensity is reduced, with an SST increase, then common squid will likely be abundant, though the intensification of the Aleutian Low and El Niño cannot be predicted.

On the other hand, in the East/Japan Sea, coldwater species such as walleye pollock will tend to be reduced in abundance. Sakurai *et al*. (2006) and Kim *et al*. (1997) hypothesized an increase in common squid and small yellow croaker abundance, based on the observation that stable and warm ocean conditions during early life stages are beneficial for those populations. Though adults show demersal behavior, young fishes (*i.e.* egg and larval stage and early juveniles) stay in the surface layer of the ocean where climate effect is at the maximum. One typical characteristic of the walleye pollock catches in Korea is the inclusion of immature juvenile walleye pollock (called small walleye pollock of ages 1-2 in Korean statistics). Juvenile walleye pollock stay in the upper layer near the coastal area. The proportion of immature pollock was higher than 90 % in the late 1970s, and it decreased continuously to 40 % in 1987, then increased to 63 % in 1990. A future warming trend of SST at spawning and nursery grounds could have a profound effect on zooplankton community as well as early life stages of walleye pollock. Larvae and juveniles might benefit from the enhanced seawater temperature and prey organisms in coastal areas, while high temperatures near spawning areas could have a negative effect on the population.

The salmon enhancement program plans to increase the number of hatchery fry released. Continuous warming in the East/Japan Sea at the time of fry release could reduce fry survival in coastal areas, so that a general warming trend in Korean waters would probably result in low chum salmon abundance and low returning rate, even though climate/environmental changes in the open ocean could improve on growth of chum salmon population (Seo *et al*. 2006). A re-location plan for hatcheries and replacement of chum salmon with species which are more resistant to higher temperature should be considered.

More than 90 % of world aquaculture products are produced in the northwestern Pacific area. In Korea, one third of marine products are currently from marine aquaculture. In general, the increase in seawater temperature accelerates physiological responses of organisms as well as degradation of environmental quality, which may result in the collapse of the aquaculture industry unless target species are changed. In particular, lower dissolved oxygen due to enhanced seawater temperature will be harmful to organisms in confined water mass such as lakes or cages.

Acknowledgements

We appreciate thoughtful advice and suggestion by Dr. D.R. Gunderson (Univ. of Washington/Pukyong National Univ.) and two reviewers. This work was supported by Pukyong National University Research Abroad Fund (PS-2005-027) in 2005.

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