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Impacts of Climate and Climate Change on the Key Species in the Fisheries in the North Pacific

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Executive Summary

This is the first report by an international group of experts that looks at the impact of climate change on key species in the fisheries in the North Pacific. Understanding the dynamics of fish populations, in general, is difficult, and linking the fisheries of the six PICES member countries to climate was a challenge. However, the authors of the reports worked very hard to produce this first report that is a summary gathered from a vast amount of information. In addition to the summaries and interpretations, there are over 330 references that will be invaluable to researchers. The species selected were key species in fisheries but in some cases, these species were chosen because of the availability of data regarding the impact of climate change on them. Not all key species were included because, in some countries, information was not available or, in some cases, the recognized expert was not able to participate in the study. Catches are reported in t and lengths are fork lengths (FL) unless indicated. Climate is considered on annual scales when linked to parameters like temperature and salinity. However, other important scales are used in this report, including the decadal scale of approximately 10 years, which is linked to trends in climate or ocean conditions, and is associated with climate regimes. Regimes and regime shifts are one of a number of modes of climate variability that include El Niño–Southern Oscillation (ENSO), on 3- to 5-year scales, as well as 30-year and 60-year scales. There is some variability in the reporting, which is to be expected. However, the main reason for this report is to assemble the information that is available to assist the science community in assessing the impact of climate and climate change on North Pacific fisheries.

The following provides a summary of the current understanding of climate change impacts of each PICES member country.

Canada

There are five marine ecosystems off the west coast of British Columbia: (1) Strait of Georgia, (2) west coast Vancouver Island, (3) west coast of Queen Charlotte Islands, (4) Queen Charlotte Sound, and (5) Hecate Strait. Sea surface temperatures measured at lighthouses around the Strait of Georgia have increased 1°C over 90 years. Climate effects on freshwater rivers and lakes are also relevant as the anadromous species of Pacific salmon commonly spawn in these ecosystems. River temperatures and discharge patterns are particularly important in southern areas, including the Fraser River, as warm summer temperatures affect the spawning of Pacific salmon. There is a climate related oscillation on land and in the ocean about the middle of British Columbia that results in opposite impacts of climate in the north and in the south. Thus, similar species may be affected differently by climate change. Decadal-scale variability or regimes have major impacts on the dynamics of key species in British Columbia marine fisheries. It was the recognition of changes in productivity of many species after the 1977 regime shift that clearly showed that climate and climate change profoundly affected key species in the fisheries off Canada's Pacific coast. A recent study indicated that the stock and recruitment relationships for sockeye and pink salmon from the Fraser River improved significantly when they were separated into regimes. In addition, the productivity or marine survival could vary considerably between two adjacent regimes. This is important, as management strategies should change when there is a shift to a low productivity regime or the population could be overfished. Regimes are generally accepted as naturally occurring climate events. It is not known how global warming will affect the frequency of regimes. One scenario is that the intensity and the storminess may increase towards the end of this century.

In general, the major fisheries on Canada's Pacific coast remain healthy. Total landings of all species increased during the 1980s and then declined to early 1980 levels. Catches of Pacific salmon that traditionally were the largest in the west coast fishery reached historic low levels by the late 1990s. Neither the increase nor the decrease was expected, but the changes are now generally accepted to be the result of climate changes.

The impact of climate change and the potential impact of global warming are considered for ten key species that accounted for 43 to 73% of the weight of the total landings from 1980 to 2000.

Sablefish (*Anoplopoma fimbria*)

Adult sablefish are abundant in coastal British Columbia waters at depths greater than 200 m. The average commercial landings from 1978 to 2002 were about 4,000 t. Catches have declined in recent years in response to fishing removals and a reduced total biomass. It is known that sablefish have decadal-scale trends in recruitment, and the recent reductions in biomass appear to be related to the poor recruitment in the relatively poor productivity regime in the 1990s. Periods of above average year-class strength coincide with stronger Aleutian Lows, more frequent southwesterly winds, below average temperatures in the subarctic Pacific, and warmer sea surface temperatures. Sablefish are long-lived with a maximum age of 113 years. Long-lived fish species are able to adapt to prolonged periods of poor recruitment, providing fishing mortality is not excessive during these periods. It is probable that global warming will not have an impact on adult sablefish, in a time frame of 50 years, that will threaten the long-term dynamics of the population. Global warming may reduce egg, larval and juvenile survival for long periods, however, if the stock is not overfished during these periods, there should be occasional strong year classes that will rebuild the population. If the Aleutian Low intensifies as a result of global warming, there is also the possibility that recruitment trends may actually improve relative to the trends in the past 50 years.

Pacific herring (*Clupea pallasii*)

Pacific herring traditionally have been a major fishery on Canada’s Pacific coast. The current fishery removes between 30,000 and 40,000 t annually, but fisheries in the late 1950s and early 1960s had annual landings exceeding 200,000 t. Presently, the abundance trends of Pacific herring are closely associated with climate-related changes in the ocean habitat. The dominant mode of variability may be the ENSO-scale rather than the regime scale. Pacific herring populations are generally healthy with the population in the Strait of Georgia at historic high levels. Off the west coast of Vancouver Island, the abundance of herring is affected by predation from Pacific hake. Global warming is expected to increase the numbers of Pacific hake that move north into the feeding areas off Vancouver Island which will increase the natural mortality of Pacific herring and reduce their abundance. Pacific herring stocks over the next 50 years are expected to continue to fluctuate in abundance as they have in the past 25 years.

Pacific hake (*Merluccius productus*)

There are two major populations of Pacific hake in Canadian waters. A coastal stock ranges from southern California to Queen Charlotte Sound. A percentage of this stock migrates north into the waters off the west coast of Vancouver Island in the summer. A smaller stock is resident in the Strait of Georgia. Canadian fishermen catch a percentage of the total exploitable biomass of the coastal stock. Although there was a gradual decline in biomass beginning in the early 1990s, catches were relatively stable at about 85,000 t during that decade. There is a small fishery for hake in the Strait of Georgia. The strait has been warming since the 1960s and at the same time hake have increased in abundance. Global warming is expected to continue contributing to the warming trend that may increase the current large biomass of Pacific hake. The offshore stock should also remain at higher abundance levels provided it is not overfished. If abundance increases, more fish will move into the Canadian zone and more will move farther north. In the summer off the west coast, more hake will also increase predation on Pacific herring.

Pacific halibut (*Hippoglossus stenolepis*)

Pacific halibut caught off the west coast of Canada are part of one coastal population that is regulated by the International Pacific Halibut Commission. Currently, the abundance of Pacific halibut is at historic high levels. There has been a small decline in biomass in the population found off Canada, but the population remains stable at historic high levels. Pacific halibut production is closely related to trends in climate and thus would be affected by changes in their ocean environment. Inter-annual and decadal-scale environmental variability are the major sources of recruitment variability under the current management strategy. The period of stronger Aleutian Lows during the 1980s was favourable for recruitment. Thus, if global warming results in a stormier North Pacific in the winter, Pacific halibut should remain at high abundances. However, recruitment into the Canadian zone comes primarily from the north, and global warming may reduce the percentage of juveniles that migrate south into the Canadian zone.

Pacific ocean perch (*Sebastes alutus*)

Pacific ocean perch is the dominant rockfish in the groundfish fishery, representing about 30% of the catch of rockfish which includes about 30 species. Pacific ocean perch have a maximum age of about 100 years, and their schooling habit makes them susceptible to overfishing. Trends in recruitment are similar to regime-related trends in climate. Fish produced during the productive 1977 to 1988 regime support the current fishery. It is important to maintain sufficient adult biomass so that the population can take advantage of periods of improved recruitment and is not seriously depleted by overfishing during periods of poor recruitment. If the frequency and intensity of intense Aleutian Lows increases, there could be increases in the frequency of strong year classes.

Pacific sardine (*Sardinops sagax*)

Pacific sardines are part of a population that spawns off California and Baja California. Sardines caught off the west coast of Canada mainly are seasonal migrants from the south. Sardine populations experience large and sudden fluctuations in abundance. The Canadian sardine fishery collapsed in 1947. It is now recognized that the sudden collapse resulted from overfishing at a time of unfavourable environmental conditions. Virtually no sardines were observed in the Canadian zone through to the early 1990s. The increases in the 1990s appear to be related to a rebuilding of the population off California after the 1977 regime shift. There is a synchrony among Pacific sardine populations around the North and South Pacific, indicating that the large fluctuations in populations are a consequence of large-scale changes in climate and ocean conditions that affect carrying capacity. The decline in the sardine population around Japan following the 1989 regime shift might indicate a decrease in the California population. Thus the current abundance and associated small fishery may be reduced naturally as the population declines following the 1989 regime shift. Global warming impacts are unlikely to change the natural cycles in abundance and could result in larger abundances moving into the Canadian zone during favourable regimes. There also may be small, residual stocks that remain in the Canadian zone all year as a result of the reduced fishery.

Pacific cod (*Gadus macrocephalus*)

Pacific cod in Canada are at the southern limit of their abundance and, therefore, are vulnerable to the expected changes in climate. In the mid-1950s, Pacific cod were common in the Strait of Georgia and off the west coast of Vancouver Island. Currently, there are few Pacific cod in the Strait of Georgia and abundances are low off the west coast of Vancouver Island. The current fishery is mainly in Hecate Strait where catches ranged from 8,879 t in 1987 to 200 t in 2001. Catches generally have been very low since the mid 1990s. Laboratory studies indicate that cod eggs do not survive well in warmer water. Bottom temperatures in February that exceed 8.5°C would most probably reduce or eliminate recruitment. Global warming will warm the bottom waters in the Strait of Georgia and off the west coast of Vancouver Island. Thus Pacific cod should gradually disappear from these areas. Stocks in Hecate Strait may also be affected, with only a few years during favourable regimes when directed fisheries could occur.

Pink salmon (*Oncorhynchus gorbuscha*)

Pink salmon currently are not highly esteemed in British Columbia, thus catches are not a good indicator of abundance. In recent years the coast-wide escapements of pink salmon may have doubled or tripled compared to abundances in the 1960s and 1970s. In the past few years, production of pink salmon from the Fraser River was at historic high levels. Favourable ocean conditions and reduced exploitation rates are probably the reasons for the general increase in abundance, although the mechanisms linking climate to the improved production are poorly understood. Pink salmon from the Fraser River traditionally account for about 60% of the total catch in odd-numbered years. The stocks in the Fraser River are close to the southern limit of their distribution. Therefore, it is expected that the current increases may be short lived. It is known that trends in climate and productivity are related, thus any intensification of the Aleutian Low could result in increased production in northern areas where river temperatures are not too warm. Basin-scale changes in pink salmon growth, survival, and straying rates may be useful indicators of large-scale climate change.

Sockeye salmon (*Oncorhynchus nerka*)

Sockeye salmon are probably the single most important fish species in the British Columbia fishery. Fraser River stocks have traditionally averaged about 80% of all sockeye salmon production in British Columbia. A recent analysis of stock and recruitment trends for the Fraser River stocks showed that productivity is associated with climate regimes. The study indicated that there was a decrease in production in the 1990s, but marine survivals improved after the 1998 regime shift. Fraser River sockeye salmon are also at the southern limit of their distribution. There is little doubt that a warming of the river and changing seasonal flow pattern will decrease the productivity of the stocks. Ocean conditions during their early marine period will also affect recruitment. However, it is difficult to predict how prey for sockeye salmon in the Strait of Georgia will be affected. In general, global warming is not good news for Fraser River sockeye whose current levels of productivity may decline.

Chum salmon (*Oncorhynchus keta*)

Chum salmon may exist in about 800 rivers in British Columbia. They are some of the last species to return to fresh water, and thus are the last species caught in the commercial fisheries. Stock assessments generally show that stocks have been relatively stable for approximately the past 30 years. Catches increased from the mid-1980s to 1990s, but declined in the late 1990s, apparently due to reduced market demand. Chum salmon in the Fraser River and around the Strait of Georgia will be more affected by the warming of freshwater spawning and rearing areas than the more northern stocks. It is probable that the productivity of wild stocks will decline. However, hatcheries produce a large number of chum fry which mitigate the impact of changes in freshwater temperatures and flows. Thus, it is the effects of a changing climate on survival in their early marine period that will be most influential. As reported for sockeye salmon, these impacts are largely unknown at this time.

Japan

Japan had the world's largest fisheries from 1972 to 1984. Catches reported by the Food and Agriculture Organization (FAO) reached a maximum of 12,820,000 t in 1984 and then declined. By 2000, catches were approximately 3.7 million t representing 5.1% of the world's catch. At present, Japan remains the largest importer of fish products in the world.

The structure and dynamics of the subarctic Oyashio current, the subtropical Kuroshio and Tsushima currents, and the transition area between the Oyashio and the Kuroshio have a major influence on the productivity of species important to the Japanese commercial fisheries. The changes in currents affect the vertical mixing of water which ultimately affects the planktonic food supply for fishes. Changes in the species composition, distribution and abundance of plankton are particularly important for the survival of larval and juvenile fishes. A doubling of CO_2 (relative to 1990 levels) is estimated to increase sea surface temperatures along the coast of Japan by 1.6°C. Along the Pacific coast the change would be 1.2° to 1.6°C, and 1.8°C along the coast of the Okhotsk Sea. If trade winds weaken, the Oyashio and Kuroshio Currents would weaken and mixed layer depth would shallow, reducing the nutrient supply to the subarctic gyre which would decrease production in the Oyashio region. Another interpretation is that the Aleutian Low would intensify, resulting in a stormier winter which would improve productivity. The impacts of climate and ocean changes are poorly understood and will vary among areas and species. It is clear, however, that climate and ocean conditions have major impacts on the productivity of key commercial fishes around Japan.

The impacts of climate change are considered for nine species that represent approximately 58 to 80% of the total catch from 1980 to 2000.

Chub mackerel (*Scomber japonicus*)

The Tsushima Current and Pacific stocks contribute to the catch. The Tsushima Current stock is distributed in the East China Sea, Yellow Sea, Bohai Sea and the Japan Sea. The Pacific stock is distributed along the Pacific coast of Japan, east to the central North Pacific Ocean, including the Exclusive Economic Zone (EEZ) of Russia. Productivity was high in the early 1970s and catches were high in the 1980s when the Pacific Decadal Oscillation (PDO) was negative and the Aleutian Low was intense. After the 1977 regime shift there was a decrease in productivity. After the 1989 regime shift productivity did not recover, possibly because of excessive fishing mortality, especially for immature fish. Productivity tends to be similar to the Japanese sardine and Pacific saury. Global warming-induced climate change will affect production, depending on how the trends in winter wind intensity changes. Warming of the spawning areas in the winter will have a negative impact on productivity as will more intense Aleutian Lows or a positive PDO.

Jack mackerel (*Trachurus japonicus*)

Jack mackerel mature at age 1 year and live to about 5 years. Catches mostly increased in the 1990s and remained over 300,000 t until 1999 when they decreased to about 200,000 t in 2002. Two stocks are recognized, the Pacific stock and the Tsushima Current stock. Both spawn in the East China Sea. There may be a relationship with the PDO in which a positive PDO (*e.g.*, in the 1980s) reduces productivity and a negative PDO (*e.g.*, in the 1990s) increases abundance.

Japanese sardine (*Sardinops melanostictus*)

Japanese sardine abundances fluctuate naturally on decadal scales, in synchrony with sardine populations off the west coast of North and South Americas. Abundance and catch of Japanese sardine drastically declined immediately after the 1988 regime shift, owing to recruitment failures. Two stocks, the Pacific stock and the Tsushima Current stock, are distinguished by their distribution and migration patterns. Distributions and spawning areas fluctuate as the population size fluctuates. Large-scale climate changes strengthen or weaken the winds and ocean currents off the coast of Japan that, in turn, affect nutrient upwelling, plankton production and larval transport. It is the mortality during the first feeding stage that primarily controls year-class strength. In the subtropical waters, deeper mixed layers typical during the positive phase of the PDO contain more nutrients in the spring and thus provide more food for the larval sardines. If unfavourable conditions persist for more than 7 years, the life span of the Japanese sardine, the population that migrates over a wide area would collapse. The coastal population would remain, but would be small as their coastal habitat is limited. The impacts of global warming depend on the change in the frequencies and intensity of regimes, which are still speculative.

Anchovy (*Engraulis japonicus*)

There is an alternating trend in abundance between anchovy and sardines, indicating that the impact of global warming will be opposite for the two species. Three stocks are recognized in the Japanese fishery: the Pacific stock, the Seto Inland Sea stock and the Tsushima Current stock. Stocks may expand off the coasts of Russia, Korea and China. Current catches are high, averaging over 317,000 t between 1990 and 2000. Global warming-induced intensification of winter winds will not be favourable for anchovy production, but weaker winds on a decadal scale will increase productivity. It is clear that climate-related trends in productivity of anchovy and sardines will be opposite.

Walleye pollock (*Theragra chalcogramma*)

Four stocks are recognized around Japan: the North Japan Sea stock, the Kitami (Okhotsk Sea) stock, the Nemuro stock, and the Pacific stock. Tagging studies show that fish migrate among these four stocks, and all stocks occur within the Russian waters. All stocks, except the Nemuro stock, have two or more spawning areas. Spawning occurs mainly in areas around northern Japan. There has been a gradual decline in catch from about 1.5 million t in 1980 to about 300,000 t in 2000. However, total catches in the 1990s were moderately stable. Ocean conditions affect productivity in trends that are approximately decadal, but the relationship does not match the traditional large-scale decadal indicators. Strong year classes are important for recruitment but the mechanisms that link with strong year classes and environmental conditions remain unknown. Walleye pollock are a moderately long-lived species and produce strong year classes which give resiliency to climate change-induced recruitment variation, provided stocks are not overfished.

Chum salmon (*Oncorhynchus keta*)

Virtually all chum salmon in Japan are reared in hatcheries and released after a short rearing period following hatching. Catches fluctuated in the recent decade without a trend, averaging about 193,600 t from 1990 to 2000. It is only the marine environment that affects productivity as there is no relationship between stock and recruitment as exists for wild Pacific salmon since the number of offspring released from hatcheries is kept relatively constant at about 2 billion. Japanese-produced chum salmon spend their first marine year in the southern Okhotsk Sea. In the fall, juveniles move into the subarctic North Pacific where they remain for 3 to 5 years. It appears that marine survival is related more to the regional conditions in coastal areas than to the PDO or Aleutian Low Pressure Index (ALPI).

Pacific saury (*Cololabis saira*)

Pacific saury have a maximum life span of 2 years or less. Two stocks occur around Japan. Most catches are from the Northwestern Pacific stock off the Pacific coast of Japan. The other stock is in the Japan Sea. The Northwestern Pacific stock spawns in winter throughout subtropical waters and in spring and autumn in the Kuroshio–Oyashio Transition Zone. Catches have been approximately stable at about 280,000 t since 1980. Productivity is related to the ENSO but does not appear to be linked to the PDO. The clear relationship of productivity with sea surface temperature in the Kuroshio and Kuroshio Extension in winter indicates that climate-related changes in the ocean will affect Pacific saury production. Warm surface waters in the Kuroshio and subtropical waters are associated with reduced recruitment which will reduce Pacific saury abundance.

Common squid (*Todarodes pacificus*)

Common squid live approximately 1 year and are abundant throughout the Japan Sea and coastal–offshore waters in the Pacific Ocean. An autumn and winter spawning stock is recognized, depending on the time egg hatching. Body size and migration patterns also differ. Both stocks are fished by Korea and China, in addition to Japan. The recent warm temperatures in waters around Japan are favourable for squid productivity which increased substantially in the 1990s. Post-spawning retention of eggs within a midwater layer improves productivity. Common squid and jack mackerel productivity are similar and opposite to the trends observed for Japanese sardine. Common squid abundances are not resilient to greenhouse gas-induced climate change as their life span is only 1 year. If there are more frequent periods of intense Aleutian Lows, there could be more frequent periods of reduced abundance.

Neon flying squid (*Ommastrephes bartrami*)

Neon flying squid are voracious predators of small fishes and squids, and grow to 60 cm in mantle length in about 1 year. A winter–spring cohort and autumn cohort are recognized on the basis of hatching times, body size and migration patterns. Neon flying squid were the target species of the former driftnet fishery that ended in 1992 by international agreement. A new jig fishery started in the mid-1990s throughout the western and central North Pacific Ocean. Since 1993, Japanese catches ranged from 15,000 t to 85,000 t. Warmer sea surface temperatures may improve production, but there is no apparent relationship to Regime and regime shifts.

People's Republic of China

China has the largest marine capture fisheries in the world, the majority of which are marine fisheries. The major marine fishing areas are the East China Sea, the South China Sea and the Yellow Sea. Much of the catch is reported by the Food and Agriculture Organization (FAO) as species aggregates such as scads which include *Trachurus japonicus*, *Decapterus maruadsi*, *Setipinna taty* and *Sardinella zunasi*. In recent years, species traditionally referred to as bycatch, and discarded at sea by other countries, have been retained and used as food in marine aquaculture. Production from aquaculture first exceeded the wild catch in 1993 and seawater aquaculture now is more than 12 million t. The Yellow Sea is one of the most intensively fished areas in the world. China now catches about 50 species that account for about 3 million t. Overfishing is recognized as a major factor affecting species composition and abundances, but there are also climate-related impacts. The East China Sea and the Yellow Sea share a common climate system. Sea surface temperatures in the Yellow Sea have a decadal pattern. The 1960s were cool, the 1970s warm, the 1980s cool, and the 1990s warm. Maximum temperatures were recorded in 1998 after which there has been a cooling trend. In general, there has been a warming trend since the mid-1950s. There is a weak relationship between large-scale climate indicators and regional sea surface temperatures as effects over land are considered to be more influential than global processes. Major rivers include the Han, Datung, Yalu, Huanghe, Sheyang and the Yangtze. The Bohai Sea and the shallow waters along the coast in the Yellow Sea are spawning areas for most species distributed in the Yellow Sea.

Small yellow croaker (*Pseudosciaena polyactis*)

The small yellow croaker is a slow growing species with a maximum age of 23 years. There are three stocks, the northern stock, the Lüsi stock, and the East China Sea stock. Most fish now mature at age one and are smaller in length than in the 1950s to 1980s. Small yellow croaker in the Yellow and Bohai seas are fished mainly by China and Korea. Catches by China declined to low levels in the 1970s and 1980s, but increased in the 1990s to the high levels recorded in the 1950s. The increase in catch in the 1990s may be related to increased productivity although it is difficult to be certain, as the fishery is not regulated. There was no indication of a major environmental change in the Yellow Sea in the 1980s when catches declined to one-sixth of those in the 1950s and 1960s. Despite these declines and high fishing effort, the low spawning abundance resulted in a recovery in the 1990s, suggesting that changes in the ocean carrying capacity resulted in the restoration of large catches in the 1990s. There are no studies examining a linkage between the population dynamics of small yellow croaker and global warming impacts. There is evidence of a connection with climate, thus it would be expected that changes in production and, perhaps, distribution could occur.

Anchovy (*Engraulis japonicus*)

Anchovy are widely distributed in the Bohai Sea, the Yellow Sea and the East China Sea with at least one stock in the East China Sea and one in the Yellow and Bohai seas. First maturity occurs at age 1 year. Peak spawning is from mid-May to late June, with most fish spawning at 1 to 2 years old. Maximum life span is about 4 years. A maximum biomass in recent years was 4.2 million t in late 1992, and prior to 1993 it appeared stable. By the mid-1990s the biomass and catch declined rapidly, and by 2001–2002 the biomass had been reduced by 90%. The fishery expanded rapidly in the 1990s, with more than 1 million t caught in 1997 and 1998. In 1998 more than 90% of the catch consisted of fish about 1 year old, indicating that the anchovy population had almost collapsed. This is evidence that abundances of anchovy and sardines follow opposite trends that are related to ocean conditions. Currently, the Japanese sardine is in decline, thus it might be expected that anchovy would increase if fishing pressure was not excessive. Similarly, changing climate could also affect abundances if there is an opportunity for the spawning stock to respond to changes in ocean conditions.

Spanish mackerel (*Scomberomorus niphonius*)

Spanish mackerel are abundant in the Bohai, Yellow and East China seas. One stock in the East China Sea spawns from April to May, and the other stock spawns in the Bohai and northern Yellow seas from May to

June. The species matures at age 1 to 2 years. Catches increased through the 1980s and 1990s and in recent years Spanish mackerel have been the largest pelagic fishery in the Yellow and Bohai seas, with about a half million t landed. Distributions are strongly influenced by water temperatures in the three seas. Currently, the fishery is mainly dependent on fish in their first ocean year, thus excessive fishing may have greater impacts than those of a changing climate. There is no information relating climate change to abundance or distribution.

Republic of Korea

There are 300 to 400 fish species in the marine waters around Korea of which over 100 species are of commercial value. Recent catches in the Yellow Sea and East China Sea have declined slightly to about 1 million t from about 1.5 million t in the mid-1980s to mid-1990s. At the same time, there has been a decline in the catch of demersal species and an increase in the catch of pelagic species. Smaller catches are made in the East/Japan Sea. Overfishing has been a serious threat to the productivity of key species. The loss of estuarine spawning areas due to habitat degradation from land reclamation and pollution also threatens productivity.

Changes in sea surface temperatures profoundly affect productivity. There had been an increasing trend in sea surface temperatures in the last 100 years that has accelerated in the last decade. Decadal-scale and ENSO-scale variability affect productivity. The recent warming trend is associated with a decline in cold-water species (*e.g.*, walleye pollock) and an increase in warm water species (*e.g.*, squid, jellyfish, mackerel). Thus, it is expected that climate change will affect the productivity and distribution of species important to the Korean fisheries.

Species identified in this summary represent about 75% of the catch since 1980. Most species have a wide range around the Korean Peninsula and can be categorized into three fish communities: a demersal ecosystem in the Yellow and East China seas (*i.e.*, small yellow croaker, hairtail); a pelagic ecosystem in the East China Sea to East/Japan Sea (*i.e.*, mackerel, squid, anchovy); and a demersal ecosystem in the northern part of the East/Japan Sea (*i.e.*, pollock, Pacific cod). Most species in these categories generally spawn in coastal areas during the spring, migrate to the north to feed during the summer, and then return south to the East China Sea in the winter.

Walleye pollock (*Theragra chalcogramma*)

Walleye pollock are at their southern limits, distributed along the coastal areas of the northern East/Japan Sea. They move south from the Russian coast to the coastal areas off Korea in the winter spawning season. The majority of pollock are in northern Korean Peninsula waters. Accurate catch data are not available, but estimates in the 1990s range from 400,000 – 500,000 t. Catches in Korea declined from a high of 165,000 t in 1981 to less than 5,000 t in recent years. The very low catches appear to be a consequence of the warmer water in the south. In addition to the reduced catch, there was a shift in season when pollock were available, from November–December in the 1980s to January–March at present. It is apparent that changes in climate that warm the ocean (at the surface and at 50–100 m depth) will result in reduced pollock abundances in the southern waters of the Korean Peninsula. However, there are decadal-scale trends in abundance, and in periods of cooler sea surface temperature, juvenile pollock would be expected in waters off Korea.

Chum salmon (*Oncorhyncus keta*)

Chum salmon hatcheries were established in 1913 on the northern Korean Peninsula. In the mid-1980s, Korea resumed the enhancement activities of chum salmon using hatcheries. It is believed that the chum salmon released from hatcheries rear in the southern Okhotsk Sea until autumn, then move to the western subarctic Pacific. Returning adult chum salmon are caught in coastal waters between October and November. Catches in 1997 were 553 t but declined to less than 51 t in 2000. Marine survival is less than 1%. High spring sea surface temperatures appear to be the cause of reduced marine survival, perhaps by affecting growth. Warmer sea surface temperatures in the future would not be expected to be favourable for chum salmon production from Korea. Chum salmon production is also related to regimes. In cooler, more favourable regimes, the fry from chum salmon produced in hatcheries have higher marine survival.

Small yellow croaker (*Pseudosciaena polyactis*)

Small yellow croaker is an important commercial species captured demersally, mainly in the East China Sea. Recent catches are below 10,000 t, with most fish being 1 or 2 years old in the fishery. Previously, the species used to mature at age 5, but recently they seem to be maturing at a younger age. Cold and variable temperatures at 75 m depth reduce productivity. However, the relationship between productivity and ocean conditions is too poorly understood to speculate on the impacts of global warming on this species.

Hairtail (*Trichiurus lepturus*)

Hairtail are a popular species for human consumption. Catches have gradually decreased from about 150,000 t in the early 1980s to less than 100,000 t in recent years. Hairtail migrate between the area off Jeju Island in the winter and the central parts of the Yellow Sea in the summer. Warmer bottom water off Jeju Island in the summer is associated with larger catches. Not enough information is available to speculate on the impacts of global warming on this species.

Anchovy (*Engraulis japonicus*)

Anchovy catches in the Yellow Sea and East China Sea have increased steadily since 1970 and now are approximately 240,000 t. Anchovy occur primarily in the warm water area of the southern Yellow Sea in the winter and migrate to the southern coast of Korea to spawn from April to August. It appears that the distribution of anchovy eggs and larvae in the summer is related to ocean conditions in the eastern waters off Korea. Warm currents that transport eggs into the coastal areas improve productivity. In Korean waters there is no evidence of an alternating trend of anchovy and sardine production. There is improved larval survival and growth when the Tsushima Warm Current is strong near the coast of Korea. A key to improved understanding of global warming impacts will be an improved understanding of the impacts of climate warming on the strength of the Kuroshio Current.

Japanese sardine (*Sardinops melanostictus*)

The Japanese sardines that are fished by Korea are part of the large population that undergoes large-scale fluctuations in abundance. The most recent fluctuation started in the late 1970s and ended abruptly in the early 1990s. Peak catches were about 180,000 t in the mid-1980s. Current catches are less than 2,000 t. It is recognized that fluctuations in abundance are related to natural changes in the climate and ocean. During peak abundances sardine eggs and larvae are distributed over large areas. If there are more frequent and intense periods of Aleutian Lows as a result of global warming, sardine production may increase, although there will still be alternating periods of high and low abundances.

Chub mackerel (*Scomber japonicus*)

Chub mackerel are distributed from the surface to 300 m in the Yellow and East China seas. They migrate south in the winter to the spawning areas between Jeju Island and Tsushima Island in the East China Sea. Chub mackerel are mainly caught by Korea, Japan and China. Korean catches increased to over 400,000 t in the mid-1990s and currently are about 100,000 t. Recruitment is related to salinity and zooplankton biomass. There is clear evidence that climate and regime shifts affect the production of chub mackerel. More intense Aleutian Lows and a positive PDO may have a negative impact on production.

Jack mackerel (*Trachurus japonicus*)

Jack mackerel are common in the Yellow Sea, the East China Sea and the southern East/Japan Sea. Annual catches increased in the mid-1980s through to the late 1990s, ranging from about 15,000 to over 40,000 t, and in recent years has been about 23,000 t. Increases in salinity in April, the volume transport of the Kuroshio Current, and zooplankton biomass are correlated with increased recruitment in the following year. The volume transport of the Kuroshio Current increased after 1977, resulting in salinity increases in the East China Sea. It is proposed that these changes resulted in increased prey for the juvenile jack mackerel in the spawning area. The increased production after 1977 also indicated a decadal-scale trend in productivity. The regime shift in 1988/89 shifted the habitat of jack mackerel southward decreasing the overlap with chub mackerel.

Filefish (*Thamnaconus modestus*)

Filefish productivity increased after the 1976/77 regime shift when the Aleutian Low intensified, resulting in increased volume transport of the Kuroshio Current and the Tsushima Warm Current. Consequently, catches increased to between about 200,000 and 330,000 t. Catches declined abruptly in 1991 after the 1988/89 regime shift and have remained at levels less than 20,000 t. If the Aleutian Low intensifies, under a global warming scenario, the volume transport of the Kuroshio Current would increase, favouring improved filefish productivity.

Pacific saury (*Cololabis saira*)

The distribution of Pacific saury is determined by sea surface temperature and salinity, and they can be found residing in higher salinity waters in the East/Japan Sea. Migration occurs within the Tsushima Warm Current system. They spawn twice a year, in the spring and in the autumn. Annual catches declined sharply from a peak of 40,000 t in 1976 to less than 5,000 t until the mid-1990s where they have fluctuated between 5,000 to 20,000 t in recent years. After the 1976/77 regime shift there was a delay in the spring bloom and an earlier than normal arrival of spawning groups of Pacific saury, causing a reduction in prey abundance for the larvae. Overfishing at the same time is believed to have accelerated the rate of decline. The abundance of Pacific saury is related more to ENSO than to the PDO, as the period of more frequent and intense El Niño's in the mid-1990s appeared favourable for Pacific saury production. This would indicate that a reduction in wind intensity, as a result of global warming, would favour Pacific saury production, but more frequent and intense Aleutian Lows would lower productivity.

Skipjack tuna (*Katsuwonus pelamis*)

Skipjack tuna range north to 44°N latitude off Japan to 37°S latitude off Australia. They are also fished in the eastern Pacific from California to Chile. Skipjack tuna spawn year round. All-nation catches of this species have increased steadily since the mid-1980s, and currently approach 1 million t. Korean fisheries occur in the central western Pacific Ocean and landings increased from about 100,000 t in 1990 to 174,000 t in 2002, representing about 20% of the catch of the five major countries competing for them. There is a relationship between ENSO and the distribution of skipjack tuna, and a key to understanding the impacts of global warming will be to look at the impacts of global warming on the frequency and intensity of El Niños in relation to skipjack tuna.

Common squid (*Todarodes pacificus*)

Common squid live for about 1 year. There are three spawning groups in Korean waters that are distinguished by summer, autumn and winter spawning. Catches in the East/Japan Sea averaged about 50,000 t until the early 1990s when they increased rapidly to about 250,000 t. The rapid increase in common squid abundance in the 1990s is related to the increased abundance of euphausiids and amphipods. Increased winter sea surface temperature also is associated with the increased productivity. If there are more frequent periods of intense Aleutian Lows, then the productivity of common squid will decrease. However, if wind intensity is reduced and sea surface temperatures increase, then common squid abundances will rise.

Russia

Catch of marine species in the Russian Exclusive Economic Zone (EEZ) increased from 1980 to 1986, and then declined. In the late 1980s and early 1990s, walleye pollock and Pacific sardine accounted for about 80% of this total catch but in the 1990s, walleye pollock abundance declined and Pacific sardine catches collapsed. However, Pacific herring catches increased from 2.5 to 25% of the total catches. In the late 1990s, pink salmon catch increased relative to the 1980s, representing 9% of the total catch.

Russian scientists recognized for a long time that inter-annual, decadal and long-term variability in the climate and ocean are major factors affecting the population dynamics of marine organisms. Natural short-term and long-term climate cycles are important. For example, 40- to 60-year cycles significantly influence the dynamics of fish populations and complicate the interpretation of impacts from greenhouse gas-induced climate change. Observations suggest that there can be interaction among climate cycles that result in cooling and warming trends as well as faunal reorganizations within ecosystems. For example, in recent years in the Okhotsk Sea there has been a cooling trend. The beginning of a cooler climate in the Far East in 1997 decreased water temperatures and increased ice development. At about the same time, large zooplankton biomass increased. There was a decline in the biomass of walleye pollock and Japanese sardine, and an increase in Pacific herring and some other epipelagic species such as capelin, anchovy and squids. Major demersal species such as cod, flatfishes and skates have also declined.

Major species in the commercial catch off Russia can be placed in two groups. One group includes Pacific salmon, walleye pollock and Japanese sardine whose productivity increases when global temperatures are warmer. Abundances increase when sea surface temperatures are warmer, as indicated by large-scale climate indicators such as the positive state of the PDO, larger ALPI, and zonal (westerly) atmospheric circulation. The other group of fishes, which includes Pacific herring, increases in abundance during periods of lower global temperatures, weak Aleutian Lows, negative PDO and meridional atmospheric circulation (north–south rather than westerly circulation). It has been proposed that the associated large-scale climate processes have a periodicity of approximately 60 years, but this interpretation is based on a relatively short time series of information. It is difficult to forecast future trends in the productivity of individual marine organisms because numerous factors interact to regulate recruitment, but it has been possible to forecast combined production in large marine ecosystems based on 40- to 60-year climate and ocean environment cycles. For example, it is expected that current levels of combined productivity will last to 2020 when it will begin to increase. Longer term projections are that the 21st century will be warmer than the 20th century and this will favour increased fish production. In general, the impacts of global warming on fish production is not a priority problem in the next few decades.

The following nine species represented over 80% of the catch from 1980 to the mid-1990s.

Pink salmon (*Oncorhynchus gorbuscha*)

Pink salmon represent about 40% of the biomass and 60% of the numbers of all Pacific salmon landings by all countries. Pink salmon are the most abundant Pacific salmon in Russia. At present, the odd-year run of pink salmon is dominant in eastern Kamchatka while the even-year run is more abundant in the western Kamchatka rivers, a behaviour that can be changeable. Pink salmon also stray more than other Pacific salmon.

Pink salmon catches increased in the 1980s and the 1990s for both even- and odd-year spawners. The average annual catch for odd-year runs was about 128,000 t. Catches were largest in eastern Kamchatka, eastern Sakhalin Island, and the southern Kuril Islands. There has been a recent increase in the productivity of even-year stocks. If this trend continues, all pink salmon catches could increase to the high levels of 1920–1930.

Chum salmon (*Oncorhynchus keta*)

In Kamchatka most chum fry enter the ocean from mid-May to early June and in the northern Okhotsk Sea they migrate to sea in late May to early June. Chum salmon migrate to the southeastern Bering Sea by late

November, although if ocean conditions are optimal, they may stay until early winter in the southern Okhotsk Sea. The Bering Sea is the main summer feeding area for chum salmon after they leave the coast. New research shows that chum salmon feed in a range of temperatures from 1.5° to 20°C that is wider than was previously thought. Ocean age 0 fish prefer water colder than 10.8°C, but older fish have been observed in warmer water. Most chum salmon spend three winters in the ocean (age 3+), although they can also do so at ages 2 to 6 years old.

The decline in production and catch from the early 1950s to the mid-1970s was reversed in the 1980s, but productivity declined again in the 1990s. The slow recovery in the 1980s relative to other Japanese and North American stocks is believed to be related to competition from hatchery-reared chum salmon of Japanese origin. Projections of future productivity trends are proposed to be related to long-term natural climate cycles.

Sockeye salmon (*Oncorhynchus nerka*)

Asian sockeye salmon populations can be grouped into early (spring) and late (summer) runs. Spawning time is related to the average time required to incubate eggs in a particular locality: the higher the water temperature, the later the spawning time. Most sockeye salmon rear in fresh water for at least one year and migrate to sea after spending one winter in fresh water or to age 2. Catches in recent years (22,800 t) were close to the historic high catches in the 1920s and 1930s when 14,570 to 39,750 t were landed. The catch of Asian sockeye salmon generally follows the trend of the combined catches of all species of Asian and North American Pacific salmon. These trends occur because of climate regimes, food competition, ecosystem rearrangements and fishing. Climate cycles influence sockeye salmon productivity, especially during the winter period in the freshwater spawning areas and in the ocean in the marine feeding areas. Catches of sockeye salmon are larger during periods when the subarctic front is more to the south.

Walleye pollock (*Theragra chalcogramma*)

Walleye pollock are a valuable commercial species in Russia. Major fisheries are located in the Okhotsk Sea and Bering Sea. In the Okhotsk Sea, walleye pollock are the most abundant commercial fish. There is an extended spawning period ranging from peak periods in March and early April in the western Kamchatka shelf through to early June on the eastern side. Spawning patterns and larval development are related to ocean dynamics, particularly to anticyclonic eddies that concentrate eggs and prevent them from being transported over large areas. Most males and females mature at ages 5 and 6 years, respectively. Annual catches were relatively stable, averaging about 1,500,000 t from the mid-1980s through to the 1990s, but catches declined in recent years. There is a relationship between abundance and the 11-year solar cycle and an 8- to10-year cycle in atmospheric circulation. Stronger year classes occur during periods of warming of the Okhotsk Sea when there is a close matching of early larval development and food supply.

In the Bering Sea, walleye pollock are the most abundant gadoid fish species. The population in the western Bering Sea is reproductively isolated from the eastern population. Hydroacoustic estimates in 2002 identified a biomass of 8.6 million t in the eastern Bering Sea and 286,000 t in the western Bering Sea. Most pollock in the fishery are 3 to 8 years old. Catches on the western shelf were relatively stable from 1976 to 1994 at about 273,000 t per year. From 1995 to 2002, catches decreased about 3.2 times and abundance remains low. In general, year-class strength is related to climate and ocean conditions during spawning and larval development. Long periods of juvenile residence under the ice in winter reduce survival. The strong inflow of warm Pacific Ocean water into the Bering Sea through the Aleutian Islands passes improves the possibility of strong year classes.

Pacific herring (*Clupea pallasii*)

Pacific herring are a widely distributed species in the North Pacific Ocean. There are a number of geographical groups of herring along the Russian coast that differ in their ecology and abundance. Most mature at age 3, live to 8 years, and spawn in the winter through to the early spring in the shallow nearshore areas. Catches are less than the maximum allowable catch, indicating that the fluctuations in abundance are related more to climate than to fishing. It is expected that there will be increased trends in productivity.

Pacific saury (*Cololabis saira*)

Pacific saury is a subtropic, epipelagic species that is distributed between Japan and the Kuril Islands in the south and the Komandor and Aleutian Islands in the north. They are common in the Japan Sea and the southern Okhotsk Sea. They reproduce throughout the year with peaks in the winter–spring in the Kuroshio Current and in the spring–autumn in the South China and Japan seas. One-year-old fish constitute most of the commercial catch. Catches increased through the 1980s, reaching a maximum of about 72,600 t in 1990. Catches declined in the 1990s to a low of 4,665 t in 1998, then increased to about 51,700 t in 2002. Pacific saury abundance is related to 19-year cycles of lunar activity which affect the position of frontal zones, current meandering and eddy formation within the spawning area. In both the Pacific Ocean and the Japan Sea, the increase in abundance is related to the intensification of the Kuroshio Current and the warming of surface waters during the winter. Conditions that improve the abundance of prey for the larvae also improves saury productivity.

Pacific sardine (*Sardinops sagax*)

Catches of sardine increased in the 1980s, reaching maximum levels in 1989 and 1990. Catches declined quickly beginning in 1991, and there has been virtually no catch since 1994. Catches in the Russian zone occur during the feeding period beginning in April through to June in areas off Primorye and Sakhalin Island, and ending in late October–early November. Five large rapid rises and declines in sardine abundance were reported over the past 500 years. It is proposed that atmospheric processes that are characterized by westerly winds produce a warmer climate and are favourable for sardine production that can result in a rapid increase in abundance. Conditions within the entire ecosystem are essential for a rapid increase in abundance. A relationship exists between abundance cycles and the 22-year cycle of solar activity. It is possible that the next rapid increase of sardine abundance will occur between 2010 and 2020 as a consequence of naturally occurring planetary processes.

Pacific cod (*Gadus macrocephalus*)

Pacific cod are widely distributed along the Pacific Rim from the Yellow Sea to Santa Monica Bay, California. They are among the larger demersal species and are highly regarded as a commercial species. They remain a major species in the coastal catch of the Russian EEZ. Spawning occurs from February to April, with peak spawning in March. Pacific cod prefer to spawn in water temperatures of 1.0–2.5°C and to avoid water warmer than 10°C. Pacific cod are characterized by extreme variability in year-class strength. Environmental factors strongly affect productivity. However, the relationship between climate, ocean conditions and productivity is poorly understood.

Red king crab (*Paralithodes camtschaticus*)

There are two populations of red king crab in the Okhotsk Sea. The western Kamchatka population is the most abundant. Seasonal migrations occur between the offshore areas in the winter and the shelf areas in the spring through to the fall when they spawn. Females retain up to 300,000 fertilized eggs for 11.5 months. Larvae hatch in April–May and settle on the bottom in August. The largest aggregations of crab larvae are found in coastal areas. Strong year classes occur every 4 to 6–7 years. The two previous strong year classes occurred in 1993 and 1994. Spawning in cold years produces low yields as larvae hatch in areas less suitable for survival. In warmer years, the larvae hatch in the warmer coastal waters where they are transported into the eastern Shelikov Bay which is favourable for growth. Abnormal ocean conditions in 1998 caused a number of apparently permanent changes in the distribution and population dynamics of bottom organisms. Cooling of the western Kamchatka near-bottom water caused crabs to change their migration behaviour, resulting in sharp declines in abundance in the north.

United States of America – Alaska Region

There are three main ecosystems in the Alaska region whose productivity are affected by their locations, topography and ocean circulation. The Gulf of Alaska, with its narrow continental shelves and deep slopes that are exposed to the North Pacific Ocean, has its productivity mostly affected by large seasonal variations in coastal circulation. The Bering Sea, a semi-enclosed high-latitude sea which has a broad continental shelf that supports high biological productivity, is unique in its seasonal coverage of ice and ocean circulation with passage of North Pacific water through the passes of Aleutian Islands. The Gulf of Alaska and Bering Sea are situated between two large continents that greatly determine their atmospheric circulations. Winter circulations are characterized by decadal-scale trends in the Aleutian Lows that link climate to productivity in both regions. The Arctic region off northern Alaska where the Chukchi Sea is ice bound virtually year round is low in biological production. There are no major commercial fisheries in the Arctic, thus the focus of this report is the Bering Sea and the Gulf of Alaska. It is recognized, however, the changes of global warming will be greatest in the Arctic.

The impacts of global warming on fish production will be difficult to separate from natural and fishing effects. Natural, decadal-scale regimes are now recognized as major influences on fish production and catch. The regime shift in 1976/77 was particularly influential in the Bering Sea and Gulf of Alaska. Large-scale indices of climate trends are useful indicators of effects on the composition and structure of ecosystems. However, no single index can adequately capture the processes that affect the dynamics of marine ecosystems. This is particularly relevant for physical–biological coupling which is known to be non-linear. One interpretation of the impacts of global warming is the secular warming of the atmosphere over the North Pacific Ocean that would decrease the meridional (north–south) thermal gradient, decreasing winter storm intensity and shifting the storm track northward. An associated increase in humidity off the Gulf of Alaska would increase coastal precipitation. The northward movements of the average line of zero wind stress curl that separated the subarctic and subtropical gyres would weaken the eastward flowing current, the West Wind Drift, shifting the bifurcation of the Alaska and Californian Currents northward.

Global warming could decrease winter storm intensity in the Gulf of Alaska, resulting in less upwelling, a shallowing and warming of the surface mixed layer characteristic of increased stratification. Predicted increased precipitation along the Gulf of Alaska would increase freshwater runoff, further increasing stratification of the surface waters. The timing of the spring bloom could be earlier, but the effect on nutrient concentrations over the shelf is not known as the possible changes would counteract each other.

Effects of global warming should be greater in the Bering Sea than in the Gulf of Alaska. Decreases in major current systems may occur, but competing effects make it difficult to forecast specific changes. Ice extent, ice thickness and brine rejection are expected to decrease. There will be increased freshwater runoff resulting from snow and ice melt and increased precipitation. Significant changes are expected, but the net effect on the ecosystem is not clear at this time. Although the Arctic is not included in this report it is important to recognize that significant changes are expected over the next 50 years. The northern ice cap is warming at twice the global rate. The extent of ice in the Arctic may be smaller by about 50% by 2100. One climate model predicts that by 2070, the Arctic may no longer have ice in the summer. Snow and ice reflect 80 to 90% of solar radiation back into space. As snow and ice disappear, more heat is absorbed by land. The very dry air in the Arctic also results in more heat being produced as less is used to evaporate the humidity. All changes are expected to have impacts on the ecosystems, including the marine fish community. One expected change is that Pacific salmon will stray more into the Arctic and some species may establish new runs in fresh water.

The effects of global warming are considered for the following key species in the Alaska marine fisheries.

Pacific salmon

Pink salmon are the most abundant species of Pacific salmon in Alaska, accounting for 40 to 70% of the annual catch. They comprised 58% of the average annual commercial catch of Pacific salmon in Alaska from

1970 to 2003. In Bristol Bay and western Alaska, pink salmon are at the northern limit of their range and are dominated by even-year runs.

Sockeye salmon are the second most abundant species in the Alaskan catch, accounting for about 27% of the annual catch in recent years. The largest fisheries occur in Bristol Bay, Cook Inlet, the Alaska Peninsula–Aleutian Islands and Kodiak regions. From 1992 to 1996, an average of 36.5 million sockeye salmon were caught in the Bristol Bay fishery. In recent years the abundances have declined substantially below previous decadal averages. The causes of the decline have not been determined but are believed to be related to changes in climate.

Chum salmon catches accounted for an average of 10% of all salmon catches from 1970 to 2003. Catches began to increase in the mid-1990s, with a record catch of 24.3 million fish in 2000. Hatcheries in the south-eastern region produce a significant percentage of the catch. However, in western Alaska chum salmon catches are well below long-term averages.

Coho and chinook salmon are popular species in the recreational fisheries. Coho catches increased from the late 1970s through to the mid-1990s and then declined slightly to 4.1 million fish in 2003. Chinook salmon catches have fluctuated between 300,000 and 400,000 fish in the past two decades, but tended to be stable, except in the late 1990s.

It is possible that the negative impacts of global warming would be more apparent to salmon production in fresh water that in the ocean. Changing patterns of river flows would affect egg survival and the timing of smolt migration into the ocean. Recent ocean conditions have contributed to greatly improve Pacific salmon productivity, indicating that climate-related changes in the ocean also have important impacts on production, perhaps not negatively. However, the potential impacts of global warming on Pacific salmon production are generally not known.

Pacific herring (*Clupea pallasii*)

Pacific herring are fished commercially mainly in Prince William Sound, Southeast Alaska, and the Togiak district. In Prince William Sound there was strong recruitment of age 3 fish in the mid-1980s. The average biomass from 1980 to 1992 was 84,000 t. In 1993, the stock collapsed and the biomass has remained at less than one half of the previous levels. In Southeast Alaska, herring biomass fluctuated without trend and without decadal-scale variability associated with standard regimes. Herring in the Togiak region exhibited a reduction in abundance in the 1980s that has remained low. The mode of climate variability that most affects recruitment is not clear, but the time of influence may be during the larval stage. The variability in recruitment makes it difficult to determine how climate change is related to production, but it may be prudent to expect the unexpected.

Alaska Groundfish Fisheries

There is decadal-scale variability in the dynamics of the Gulf of Alaska ecosystem as indicated by the changes that occurred after the 1976/77 regime shift. In general, there was a warming trend that was favorable for species such as Pacific salmon, Pacific cod and flatfishes (especially Pacific halibut and virtually all of the flatfish species, except for deep-water Greenland turbot in the Bering Sea slope region), Pacific ocean perch and other rockfish species, but was unfavorable for crustacean species such as shrimp and crab. Ecosystem responses were less dynamic after the 1989 and 1998 shifts, indicating that climate changes are important, but there is considerable variability between the linkages of these climate shifts and the recruitment responses of the key commercially important species. The main species of groundfish in the fishery are walleye pollock, Pacific cod, yellowfin sole, northern rock sole, Pacific ocean perch, Atka mackerel, arrowtooth flounder, and sablefish. The dominant species in the catches in the Bering Sea were walleye pollock (73%), Pacific cod (11%), yellowfin sole (4%), northern rock sole (3%), Atka mackerel (3%) and the rest were less than 1% each. The average catch from 2002–2004 was about 1.9 million t from an exploitable biomass of about 18 million t. In the Gulf of Alaska, recent catches averaged 120,000 t from an exploitable biomass of 5.2 million t. The biomass is dominated by arrowtooth flounder representing 50% of all the groundfish biomass. Walleye pollock are the major commercial catch representing 36% of the landings, compared to 25% for Pacific cod, 14% for flatfishes, 13% for rock fishes, and 8% for sablefish. Catches are at near historic high levels, even though they generally are below acceptable levels. Strict catch limits are placed on all species, including bycatch, to reduce the unintended catch of other species. Walleye pollock, Pacific cod, Atka mackerel and sablefish had similar trends in production, but not on a scale of the standard regimes. However, flatfish and rockfish production corresponded to a regime-scale pattern.

Walleye pollock (*Theragra chalcogramma*)

Walleye pollock are the key commercial species in the Alaskan fishery. There are three main stocks in the Bering Sea–Aleutian Islands (BSAI) region, the eastern Bering Sea stock, the Aleutian Basin stock and the Aleutian Island stock. There are two main stocks in the Gulf of Alaska. There are a number of spawning areas in the BSAI, within the major spawning areas over the shelf. Pollock that spawn in the open ocean have their eggs and larvae carried by currents over a wide geographical area, beginning in late February. Recruitment is largely determined by the end of the larval period. In general, survival is diminished when larval fish are transported offshore, and increased if the eggs and larvae are carried towards the shelf where food is more plentiful. It is generally agreed that the frequency of occurrence of strong year classes determines the population biomass. There is no indication that recruitment is related to regimes and regime shifts although there was a major increase in biomass in the 1980s following strong recruitment in the late 1970s. The increased production may be a result of warmer temperatures, reduced ice cover at spawning times and increased plankton production for larval fish. In contrast, walleye pollock biomass in the Gulf of Alaska declined from a maximum in 1982 through to the present. Occasional strong year classes occurred about every four years in the 1980s and 1990s which may be related more to ENSO conditions than decadal-scale variability. There is an improved understanding of the mechanisms that cause variation in recruitment, but there are still a number of hypotheses that need to be resolved. The matching of prey with larval feeding is the major consideration, but cannibalism and distributional changes resulting from ocean temperature changes are also considered important. An important consideration is that the variability in recruitment is climate related. The impact of global warming would be related to changes in currents that transport eggs and larval pollock. Until more is known about the changes in currents, it will be difficult to determine the impacts of a warming climate on walleye pollock productivity.

Pacific halibut (*Hippoglossus stenolepis*)

The center of Pacific halibut abundance along the west coast of North America is the central Gulf of Alaska. They begin to mature at age 8 and about 50% are mature by age 11. Spawning occurs from November to March in the deeper waters near the edge of the continental shelf off Alaska. Eggs and larval fish drift westward and northward for 6 to 7 months after spawning. It is at this stage that climate and ocean conditions determine the strength of the year class. The commercial fishery is shared with Canada and managed by the International Pacific Halibut Commission. Catches increased in the 1980s and in recent years have been at historic high levels of about 40,000 t. Climate variability affects productivity and distribution of halibut. There also have been major changes in trends in weight that are not readily associated with stock size. Female halibut at age 11 in 1995 were roughly half the weight they were in 1980. Recruitment is primarily related to climate regimes as indicated by the PDO. Stock size explains very little of the variability in recruitment. Recruitment into the Alaskan fisheries improved relative to other areas during the positive phase of the PDO. Global warming impacts that affect the ecological and oceanographic conditions in the near surface waters during the egg and larval fish period will have the greatest impacts on production. However, the impacts on ocean circulation in the surface waters along the shelf edge are not well understood.

Crab

Three king crab species, red, blue and golden brown, and two Tanner crab species, Tanner and snow, are major fisheries off Alaska. Recent averages yields for king (8,130 t), snow (13,038 t), and Tanner (712 t) crabs are well below the long-term averages. Catches of crabs are restricted by regulation to large male crabs. Current crab abundances are low. Abundances of most red king crab populations have been low since the mid-1980s.

Blue king crab abundances are very low, resulting in an overfished designation in the Bering Sea. The Eastern Bering Sea Tanner crab population declined in the early 1990s. The fishery has been closed since 1996, with the exception of a small fishery near the Pribilof Islands in recent years. Eastern Bering Sea snow crabs are also in low abundance.

Fluctuations in crab recruitment at the egg and larval stage are the causes of the changes in abundance. There is some evidence that intense Aleutian Lows reduce larval survival as preferred diatom species are less available. However, there is poor correlation in recruitment patterns among stocks, indicating that the relationship with climate is complex. With no common explanation for all stock changes, it is difficult to predict how ocean warming would affect future crab recruitment, particularly when crab larvae and young crabs are subject to predation and other ecosystem interactions. There have been major shifts in the spatial distribution of Bering Sea red king crab in the last three decades. Shifts in distributions seem to be related to warmer near bottom temperatures. These shifts may affect the subsequent distribution patterns of eggs and larvae. Understanding the impacts of global warming requires a better understanding of the mechanisms that affect larval survival as well as an understanding of changes in near bottom temperatures and new current patterns.

Pandalid shrimp

Shrimp (*Pandulus* and *Pandalopsis* spp.) landings in Alaska consist of five species, with the northern shrimp being the most important. Shrimp landings increased to 58,000 t in 1976 and declined rapidly to 2000 t in 1984 where they have remained at these low levels. The synchrony in the decline is an indication that changes in the ocean caused the decline. In fact, rapid pandalid shrimp population changes are one of the early indicators that the structure of a community is changing. Sustained future strong recruitment will require a shift to colder ocean conditions which could occur during a negative phase of the PDO.

Foreword

This report summarizes the interpretations of the impacts of climate and climate change on the important marine species in the commercial fisheries of Canada, China, Japan, Korea, Russia and the United States. Leading experts in these six PICES member countries used published literature as well as their own interpretations to assess the impact of climate and climate change on the dynamics of the key commercial species and their associated marine fisheries. It has been relatively recently that climate has been recognized as a significant factor in the regulation of abundance trends of key species in world marine fisheries. Thus, the literature that is available to evaluate future climate impacts is sparse. Adding to the complexity of forecasting impacts is the uncertainty related to regional climate-induced changes in the ocean habitats and the relatively poor understanding of the natural history of many species.

The Climate Change and Carrying Capacity (CCCC) Program was the principal activity of PICES since the Second Annual Meeting of the Organization in 1993. The two major themes of the CCCC Program were the estimation of the carrying capacity of higher trophic levels and the determination of how changes in ocean conditions affect the productivity of key fish species in the subarctic Pacific. The highly relevant and challenging goal of discovering how to forecast the impacts of climate change on the productivity of key fish species and their prey was set. During the 1990s, PICES established expert teams to focus on understanding the ecosystem impacts of climate change. Symposia, workshops and meetings improved scientific understanding around the North Pacific through timely and effective communication within the ocean science community. Working Group 16 on *Climate Change, Shifts in Fish Production, and Fisheries Management* was part of the effort, accepting the challenge of reporting the impacts of climate change on the key species and their fisheries in the countries that form PICES.

There is informed speculation in this report that highlights what might happen to major fisheries in the future. There also are differences in opinion. However, this international summary should be seen as a first attempt to report what is known about the impact of climate and climate change on the major fisheries in the northern North Pacific. It is a benchmark that can be cited and used to encourage the formation of other research teams. Not all key species or major areas were addressed by all countries, but there is an accumulation of material that provides evidence of large-scale associations with climate. An effort was made to standardize the reporting among countries; however, the reader will note that structural and editorial differences occur. Also, the issues were seen differently among the scientists involved in the preparation of the report. These differences were to be expected as the approaches to fisheries management differ among the six countries. The Synopsis attempts to tie everything together by emphasizing how the major species and their fisheries may be related to large-scale climate events. This section is the interpretation of the two authors and not necessarily the view of all authors. I hope that it is the Synopsis that leads to the next report which will bring experts together to search for common mechanisms and linkages. Success in this second phase could lead to the third phase, which would connect information to global climate change models and natural physical cycles.

In the future, there needs to be better understanding of the biology, ecology and population dynamics of the key species in the major fisheries in the North Pacific. An improved understanding of the natural history of the major species will improve forecasts and may reduce the number of models used to make decisions. Readers of this report will be able to appreciate the amount of work that is involved to develop forecast models that reliably identify the impacts of future climates. It is clear from the experience of this Working Group that forecasting the impacts of a changing climate on the key fisheries in the North Pacific will require commitments by all countries to support coordinated and focused research by teams of experts.

R.J. Beamish

Abstract

This is the report of the PICES Fishery Science Committee Working Group on *Climate Change, Shifts in Fish Production, and Fisheries Management* (WG 16). There is general agreement that climate change strongly affects the production of many species around the North Pacific and that the impact of greenhouse gas-induced changes on key species and their fisheries are poorly understood. Some PICES member countries consider global warming effects on fish populations to be less important than fishing impacts and natural climate cycles.

The productivity of key species in the fisheries off Canada is generally recognized to be related to climate and climate change. Regime-scale changes in climate variability affect many important fisheries. If global warming results in more frequent and more intense Aleutian Lows, as might be indicated by climate change trends since the 1970s, then the productivity of the many species that had increased marine survival in the 1980s may improve. However, species at the southern limits of their distributions may decline even if there is an intensification of the Aleutian Low.

A major influence on fish productivity in the Japanese coastal and offshore fisheries is the structure and dynamics of the subarctic Oyashio current, the subtropical Kuroshio and Tsushima currents, and the transition area between the Oyashio and the Kuroshio. Climate and ocean conditions are known to have major impacts on the abundance of key species in the Japanese commercial fisheries. If winds are reduced by future warming of the ocean, the primary production in the seas around Japan may also decrease because of reduced vertical ocean mixing in the winter. In general, however, the impacts of climate and ocean changes vary among areas and species, and are poorly understood, but it is clear that climate and ocean conditions are major influences in the productivity of fishes in the seas around Japan. Thus, it is predicted that global warming-induced changes will affect future fisheries.

The People's Republic of China has the largest marine fisheries in the world. It also has the largest sea water aquaculture production that exceeds their wild catch. Climate and ocean conditions are known to affect production and distribution, but fishing is considered to be the major factor influencing the population dynamics of key commercial species. There are distinct patterns in ocean temperatures that appear to be a result of regional rather than global influences.

Catches of marine species by the Republic of Korea (most commercially important species range around the Korean Peninsula) were relatively stable from the late 1980s to the mid-1990s and have declined slightly in recent years. Overfishing has been, and continues to be, a serious threat to productivity, resulting in populations of smaller, very young individuals. Climate-related ocean changes also profoundly affect productivity. It is recognized that future climate change will have important impacts on productivity which will require reducing the effects of overfishing. However, the impacts of global warming are speculative.

Climate and ocean conditions have traditionally been a major consideration in Pacific fisheries science in Russia. Natural cycles in atmospheric circulation, sea surface temperatures, lunar and solar cycles are all associated with the aggregate productivity of marine ecosystems. In particular, it appears that there is a natural 50- to 60-year periodicity that is proposed to continue to influence fish productivity in the 21st century. Russian fisheries scientists assess global warming impacts relative to these natural cycles. Because these cycles are so influential on physical and biological processes in the ocean, global warming impacts are not considered as the first priority problem, at least for the next few decades, especially because the Far Eastern seas have cooled in recent years.

There is convincing evidence that natural climate-related changes strongly affect the dynamics of key commercial species in the United States fisheries off Alaska. A major change in ecosystem dynamics and species composition occurred after the 1977 regime shift, indicating the importance of large-scale climate changes that can be relatively fast. It is generally agreed that future climate change will alter the ecological dynamics of marine ecosystems but the mechanisms that regulate recruitment are so poorly understood that it is difficult to do more than speculate on the impacts of global warming.

Synopsis

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This study identified climate and ocean conditions as major factors affecting the dynamics of key species in the fisheries of Canada, Japan, People's Republic of China, Republic of Korea, Russia and the United States of America. Trends in production or catch were evident, possibly indicating that the environmental effects were not random. However, the scale of climate influence varied among areas and species.

Pacific Salmon

The general trend in Pacific salmon production was similar for North American and Asian populations. Increased production started in the late 1970s, reaching historic high catches in 1995 (Fig. 1). Catches declined slightly but were the second highest in history in 2003. In both the eastern and western Pacific, salmon catches generally increased substantially after the regime shift in 1977. Pink salmon dominate the Russian catch, which increased throughout the late 1980s and into the 1990s. Japan produces the largest number of chum salmon, virtually all in hatcheries, eliminating climate impacts in fresh water. However, it is recognized that juvenile chum salmon produced in Japan rear in the Okhotsk Sea, Bering Sea and Gulf of Alaska in the winter. Thus, ocean conditions throughout the subarctic Pacific influence returns through marine survival. The mechanisms responsible for the increases in salmon abundance, beginning in the late 1970s, are not clear as total salmon production relates to conditions in fresh water, the ocean, as well as to hatchery production. Adding to the complexity is the relative absence of stock-specific catch and escapement measurements. Despite these difficulties, there is evidence that the effects of climate and ocean conditions on salmon production are not random. For example, in a recent study (Beamish *et al.*, 2004), the aggregate production of all sockeye salmon in the Fraser River in Canada shows a clear trend in the residuals from a Ricker curve fit to stock and recruitment data. The change in the trends in this important Canadian population was consistent with a regime scale of variability. Another example is the increased pink salmon production in Russia that was associated with a warmer ocean and with trends in atmospheric circulation. If the favourable conditions persist, pink salmon catches may continue to increase, reaching the high levels of the 1920s (Radchenko, 1998).

Although there was agreement within the PICES Working Group on *Climate Change, Shifts in Fish Production, and Fisheries Management* that climate was an important factor affecting salmon population dynamics, it was not possible to determine how future climate scenarios would affect total and regional salmon production. Various levels of speculation exist, but the only firm conclusion is that climate will continue to be a major factor affecting salmon production in a non-random manner. If dependable forecasts of climate impacts are important in management, it is clear that more information is needed about the mechanisms that limit their freshwater and marine production. It is also important to recognize that hatcheries provide a method of mitigating unfavourable conditions in fresh water and, to some extent, allow for a better matching of the time of entry into the ocean and prey availability.

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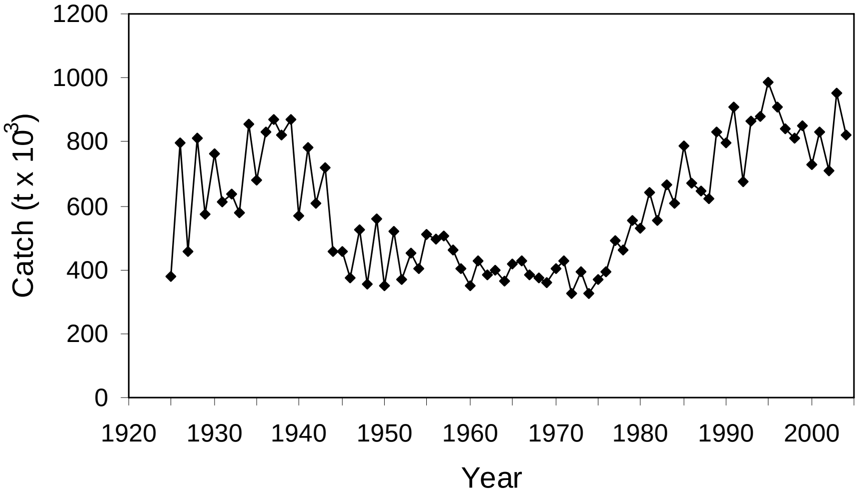

Fig. 1 Total catch of Pacific salmon by Canada, Japan, Russia and the United States from 1925 to 2004.

Other Important Species

In the eastern Pacific, important fisheries exist for walleye pollock, Pacific cod, Pacific hake, Pacific herring, Pacific halibut, sablefish, and Pacific ocean perch. In the western Pacific, the key species in the fisheries are walleye pollock, Japanese sardine, anchovy, Pacific herring, chub mackerel, jack mackerel, Pacific saury, small yellow croaker and hairtail. In general, fisheries for all these species represented about 57.3% of the total catch in the northern North Pacific in the 1990s (FAO, 2006).

Walleye pollock support the largest fishery in the northern North Pacific, representing 23% of all recent fish catches, including Pacific salmon. It is the world's largest fishery, accounting for 8% of all marine fish catches in the 1990s. It is the dominant fish in the Bering Sea and Okhotsk Sea. There are trends in its abundance that are approximately decadal, indicating that trends in climate and ocean conditions affect recruitment. In the Bering Sea, abundances increased in the mid-1980s and then decreased to the mid-1990s. Abundances have decreased recently in the eastern Bering Sea and western Bering Sea. There is a trend in production but the timing of fluctuations in the Bering Sea and Okhotsk Sea has not been found to correspond to the generally accepted years when regimes have shifted (1977, 1989 and 1998). This may indicate that other trends in forcing factors are important, or that the information used to date to detect an association is incomplete. In the Okhotsk Sea, periods of warmer water appear to provide more prey for the larval stages of pollock, improving recruitment. This explanation is similar to the proposal of Hunt *et al.* (2002) that cold regimes in the Bering Sea reduce prey abundance for larval pollock, resulting in trends of reduced pollock abundance. There is a similarity in trends of recruitment between walleye pollock and Pacific cod in the eastern Bering Sea and Gulf of Alaska, indicating that common factors in the ocean are synchronously affecting their production. It would appear that the basic biological mechanisms linking recruitment and environmental factors are similar throughout their distribution. However, the mechanisms remain to be identified. It is clear that there are trends in abundance that are linked to trends in the ocean which would be expected to be linked to trends in climate. Considering the importance of pollock, it would seem logical that an international team of researchers should be formed to coordinate the research and analyses needed to establish the linkages between climate trends and walleye pollock recruitment. This is also a necessary step towards understanding the impacts of future changes in climate trends.

Pacific cod represented approximately 6% of the total groundfish catch in the northern North Pacific in the 1990s. In 2002–2004, this species accounted for 11% of the United States groundfish catch in the Bering Sea and 25% in the Gulf of Alaska. These catches were the second highest of all species. In Russia, Pacific cod traditionally have been the fourth highest species in the catch, including Pacific salmon. It is interesting that the total catch of Pacific cod from 2002 to 2004, as reported by the Food and Agriculture Organization (FAO) of the United Nations, is approximately 40% of the total catch of Atlantic cod (*Gadus morhua*). Despite the importance of Pacific cod, there was surprisingly little information about the factors affecting recruitment. Canada reported that recruitment was related to ocean conditions. Russia identified strong fluctuations in year-class strength but had difficulty linking these fluctuations to environmental factors. The United States noted that Pacific cod and walleye pollock have similar recruit per spawner trends in the Bering Sea and Gulf of Alaska, suggesting that there is a common mechanism linking their productivities. Pacific cod population dynamics need more attention, particularly if their dynamics are a good index of changing ecosystem states, as suggested by Canada.

Pacific herring are another commercially important species around the rim of the northern North Pacific. Canada, the United States, Russia and China identified Pacific herring as a major species in their fisheries. Pacific herring are also a key prey for a number of other species, including marine mammals. There was consensus that abundance trends occurred, but perhaps not on a decadal scale. Stock and recruitment relationships were unclear, but environmental conditions appeared to be the critical factor influencing recruitment. Temperature generally provided a useful index of recruitment patterns. For example, herring populations off the Russian coast were large during periods of weak Aleutian Lows and cooler ocean temperatures. In general, the pattern of trends in herring abundance was opposite to abundance trends for walleye pollock and Pacific sardine and also differed from other species, such as Pacific cod and Pacific salmon. Canada and China identified relationships between herring and the Southern Oscillation which may also be related to temperature impacts on recruitment. It is important to determine how temperature acts to affect recruitment, as warm temperatures were favourable for one population and unfavourable for another population off Canada. Both prey abundance and predator impacts appear important, suggesting a wasp-waist type of population dynamics. There is no question that excessive fishing can reduce recruitment by depleting spawning stocks, but there is equal certainty that populations can increase quickly. The general conclusion is that low frequency variability in ocean and climate conditions may regulate recruitment of Pacific herring. Unfortunately, decades of research have failed to clearly identify the mechanisms involved. Thus, any forecasts of global warming impacts on Pacific herring remain as educated speculations. As recommended for walleye pollock, it would seem to be timely for an international group of experts to meet in order to determine what information is needed to be able to assess the impacts of global warming on Pacific herring.

Fisheries for Pacific hake (also referred to as Pacific whiting) are the largest of all fisheries off Canada and off the states of Washington, Oregon and California. The United States did not include fisheries off the coasts of these states in their report, but Canada reported on this coastwide fishery and on a population of Pacific hake in the Strait of Georgia. In the Strait of Georgia, a general warming trend appears to be favourable for Pacific hake production. However, other changes, such as a reduction of predators, may have contributed to the current large abundances. The offshore population of Pacific hake has a pattern of recruitment that remains to be understood. A number of studies and papers have attempted to unravel the linkages regulating recruitment, but to date, these linkages remain vague. Forecasting future trends in abundance will require a better understanding of mechanisms regulating production if long-term forecasts are to be useful in management.

Pacific halibut generally have trends in production that follow a decadal-scale variability that matches the standard regime periods marked by regime-shift years in 1977, 1989 and 1998. The assessment of Pacific halibut was perhaps the first to incorporate the regime scale of variability. Pacific halibut are at the top of the food chain; they are large fish and their abundance is currently at historic high levels (Clark and Hare, 2002). The changes in abundance trends appear independent of stock size (Clark and Hare, 2002), but there is a major reduction in growth. The increase in abundance from 1980 to 1995 was associated with about a 50% reduction in the size of mature female halibut. The impacts of climate and ocean conditions on survival are believed to occur in the near surface waters when larval halibut are being transported northward. The linkages remain to be discovered.

Owing to high prices, sablefish are an extremely valuable species in the Pacific coast fisheries of Canada and the United States. It is known from Canadian studies that sablefish have decadal-scale trends in recruitment that change near the recognized time of regime shifts. It is also known that there can be a coast-wide synchrony in strong year-class production. Periods of above average recruitment occur when a regime is characterized by intense Aleutian Lows. A recruit per spawner analysis of sablefish in the Bering Sea and Gulf of Alaska detected trends in recruitment and a shift about 1976–1977, but not the same pattern observed by the Canadian study. Strong year classes are a major factor in recruitment, occurring when there are abundant copepod nauplii at the time larval sablefish begin to feed. Understanding how global warming will affect sablefish production, therefore, may require an understanding of how climate and ocean conditions affect the production and timing of production of copepods. Sablefish are long-lived, with a maximum age of 113 years, and this may tend to buffer the affects of climate change. Long-lived species are able to adapt to prolonged periods of poor recruitment as long as they are not overfished. This may mean that fishing strategies for sablefish need to incorporate the importance of the age structure in a population (Beamish *et al.*, 2006).

Pacific ocean perch are the dominant species in the catches of a number of species of rockfish. There is a tendency to think that because the 20+ species that are fished are all called rockfish, that there are common mechanisms regulating their productivity. While there may be some validity in this assumption, it would be wise to determine the extent of the similarities before assuming common impacts of climate. Pacific ocean perch in the Canadian and United States fisheries showed a decadal-scale variability in productivity that changed around the regime shift years of 1977 and possibly 1989. Pacific ocean perch are long-lived, with maximum age of about 100 years, and this may mask the effects of climate change. The period from 1977 to 1988 appeared favourable for recruitment. Thus, periods of intense Aleutian Lows may increase abundances, provided that the species are not overfished during periods of poor recruitment.

It is important to recognize that fish in the major fisheries of China, Japan and Korea have much shorter life spans than many of the species off the coasts of Canada and the United States. Off Canada's coast, for example, Beamish *et al.* (2006) reported that 58% of the 59 species with fisheries of ≥ 1 ton had life spans greater than 30 years. This is important because it is believed that longevity reflects an evolved response to the modes of climate and ocean variability that affect recruitment.

Sardine and anchovy populations are well recognized as responding synchronously and rapidly to changes in their ocean environment throughout the North and South Pacific oceans (Kawasaki, 1983). The cycles of abundance alternate (Chavez *et al.*, 2003) in response to large-scale, rather than regional climate changes. Fishing is not the factor that drives abundance, except that fishing may affect the rate of increase or decline. In the North and South Pacific, the largest total sardine catch in 1985 was 18% of the total world catch of all marine fish. World supplies of fish meal and fish oil depend on this catch, which is of economic value to regional fisheries. Thus, it is important to be able to understand how climate can simultaneously and rapidly cause massive increases and decreases in abundance. It is known that periods of intense Aleutian Lows are favourable for Japanese sardine production and unfavourable for anchovy production. The shifts in trends occur about the time of recognized regime shifts, indicating that the winter wind intensity and atmospheric circulation patterns are important. Russian scientists report that the regime-related shift to zonal winds is associated with the rapid increase of sardines. They also find close associations between productivity trends and the 22-year solar activity cycle.

Pacific saury are a sub-tropical species that have accounted for total catches in the western Pacific ranging from 163,000 t in 1970 to 491,000 t in 1973. Catches declined in the 1980s and increased again to 436,000 t in 1990. This was followed by another decline to 181,000 t in 1998. In 2003, catches increased to 446,000 t. Pacific saury have a productivity pattern that indicates an association with climate cycles. Russian scientists propose that trends in abundance are related to lunar cycles. Others found associations with the El Niño–Southern Oscillation (ENSO), reporting that improved abundances were associated with the frequent El Niños in the mid-1990s. It also appears that intense Aleutian Lows associated with a positive Pacific Decadal Oscillation (PDO) result in reduced abundances. Thus, there may be a relationship with climate, especially winter climate, but the mechanisms linking climate to production are not known.

Species associated with the Korean and Chinese fisheries are difficult to study because of their history of intense fishing pressure. Nevertheless, there is evidence that climate and climate shifts have important impacts on the productivity of chub mackerel and jack mackerel. Jack mackerel productivity is negatively related to the PDO. A positive PDO was associated with reduced abundances in the 1980s and a negative PDO with increases in the 1990s. This relationship with the PDO appears to be a function of the southern limit of the Oyashio Current which is also negatively related to the PDO.

Chub mackerel abundance was shown to be related to climate and climate shifts. In general, a positive PDO and intense Aleutian Lows are associated with reduced productivity, as evidenced by the reduced abundance after the 1977 regime shift. Little is understood about the mechanisms regulating the production of small yellow croaker and hairtail. It is known that anomalously warm bottom temperatures are associated with improved production.

Red king crab have supported valuable fisheries in the eastern and western Pacific and populations may be categorized as heavily fished. Strong year classes are important to maintain these populations. Off Alaska, all strong year classes occurred before the 1977 regime shift, when the Aleutian Low was weak. Off the Russian coast, eight strong year classes in the past 25 years provided much of the recruitment that supported fisheries. Reduced recruitment occurred during periods of strong Aleutian Lows, suggesting that there is a common process affecting strong year-class development in the eastern and western North Pacific. Russian studies identified a relationship between good larval survival and the opportunity of the crabs to spawn in shallower coastal depths of 30 to 50 m. Migration into these areas was related to bottom temperatures which are linked to oceanographic conditions affecting near-bottom currents. Mystery still surrounds the explanation for the mechanisms regulating their productivity, but it does appear that environmental factors are important, and there may be a relationship to the decadal shifts in the Aleutian Low. Zheng and Kruse (2000) proposed that the diatoms that are important for first-feeding red king crab larvae are more abundant in years of light winds or weak Aleutian Lows when the water column is more stable.

Common squid support major fisheries in Japan and Korea. Abundances were high in the 1960s, declined in the 1970s through to the 1990s when there was a substantial increase. The life span of common squid is approximately 1 year, thus, trends in their abundance are good indicators of changes in ecosystems. Warm winter sea surface temperature appears to increase the spawning area, improving production. There is a positive relationship between increased abundance of squid and euphasiid and amphipod abundance in the plankton. The historic abundance trends are negatively related to the PDO, similar to trends in jack mackerel and opposite to trends in Japanese sardines.

Trends in Major Fisheries

We selected the major fisheries that were represented in this report to determine if the trends in catch were associated with decadal-scale trends in climate. The species selected were the key species in the study area and, where possible, were common on both sides of the Pacific. Catch information for Pacific salmon came from the North Pacific Anadromous Fish Commission (www.npafc.org) and for other species, from the Food and Agriculture Organization (www.fao.org). Our analysis relates only to the dynamics of the fisheries for the period 1970 to 2004. The population dynamics of the species in the fisheries was not specifically considered in the analyses.

For each species considered, we estimated the standardized catch anomalies for each year by subtracting the time series mean and dividing by the standard deviation of the catch. The anomaly for each species was then lagged by the number of years it would take for the species to be recruited into the fishery (Table 1). We then looked at the sign of the standardized anomalies to see if particular species grouped together by exhibiting similar trends of positive or negative anomalies. Four groups were identified using this process, and the anomalies for species within a group were summed to produce the overall group anomalies which could be compared across groups (Fig. 2). The pattern of anomalies for Pacific herring almost mirrored (opposite in sign) those of Pacific sardine and walleye pollock, so the inverse anomalies (changed sign) for Pacific herring were used, and the three species were included in the same group.

Table 1 Lag times used to estimate the years from hatching to recruitment to the fishery.

Group 1		Group 2		Group 3		Group 4	
Species	**Lag (yrs)**	**Species**	**Lag (yrs)**	**Species**	**Lag (yrs)**	**Species**	**Lag (yrs)**
Pacific cod	+2	Hairtail	+1	Chinook salmon	+3	Pacific sardine	+3
Pacific hake	+2	Anchovy	+1	Coho salmon	+1	Walleye pollock	+3
Pacific halibut	+7	Yellow croaker	+1	Chub mackerel	+1	Pacific herring*	+2
Sockeye salmon	+2	Jack mackerel	+1	–	–	–	–
Pink salmon	+1	–	–	–	–	–	–
Chum salmon	+3	–	–	–	–	–	–

* Inverse relationship (anomalies) between Pacific herring and the other two species (Pacific sardine and walleye pollock) in Group 4.

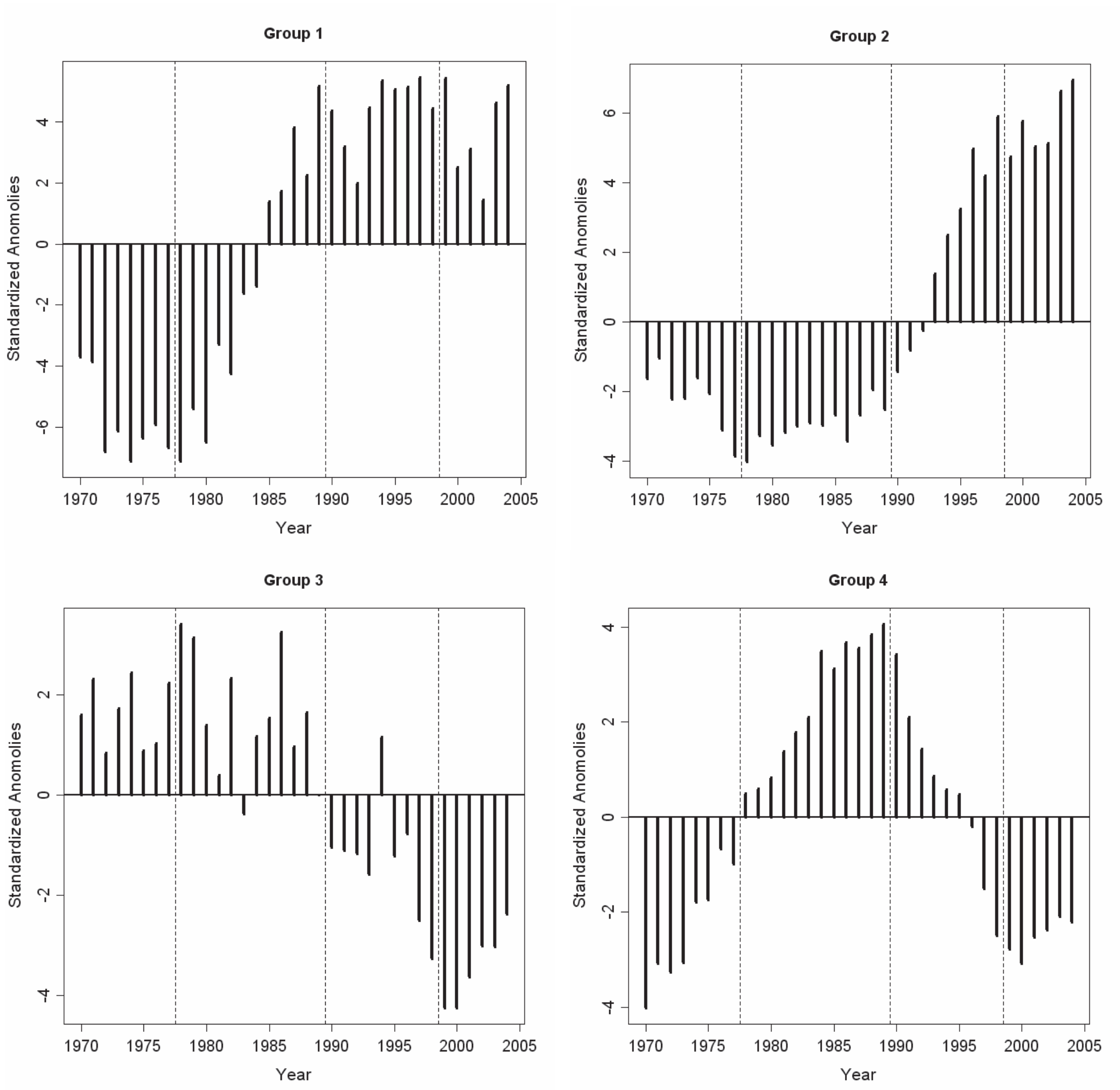

Fig. 2 Summed standardized anomalies for species within the four groups identified in this study. The anomaly for each species was lagged by the number of years it would take for the species to be recruited into the fishery. The dashed vertical lines represent the timing of the major regime shifts of 1977, 1989, and 1998.

Table 2 Run tests for the four groups.

	Standardized normal	**p-value**
Group 1	– 5.6583	1.529×10^{-8}
Group 2	– 5.6431	1.670×10^{-8}
Group 3	– 4.2563	2.079×10^{-5}
Group 4	– 5.3183	1.047×10^{-7}

Run tests (Siegel and Castellan, 1988) were done to determine if there were trends in the group anomalies. For each set of group anomalies, a binary sequence was generated with +1 being assigned for positive standardized anomalies and –1 for negative anomalies. A run consists of one or more consecutive positive (or negative) values before the binary time series changes sign. If the number of runs in the time series, r, is much smaller than the length of the time series, n, then there is evidence to suggest that the time series is not random. The tests confirmed what is visually obvious in Figure 2 that there is strong evidence for runs in each of the four groups (Table 2).

In most cases, there is no clear reason why the species fall within a specific group. It could be that the species have similar life histories or occupy similar ecological niches. It could be that their response to climate change is similar and related through some complex ecological process or that the fisheries are managed in a similar fashion. It could also be that similar responses for species are entirely coincidental, a function of the criteria used for creating the groups, or that stock-specific responses (*i.e.*, geographic differences) are blurred by averaging the responses for the entire species.

Group 1 (Pacific cod, Pacific hake, Pacific halibut, sockeye, pink, and chum salmon) contained fisheries that generally were larger during periods of intense Aleutian Lows (or positive PDOs). Catches increased fairly rapidly following the 1977 regime shift and have generally been above the 1970–2004 average since the mid-1980s. Group 2 (hairtail, anchovy, yellow croaker, and jack mackerel) fisheries generally increased as well following the 1977 regime shift although perhaps at a slower rate than those species in Group 1. The Group 2 species exhibited a more intense response to the 1989 regime shift and have remained at fairly high levels of abundance. Group 3 fisheries (chinook and coho salmon, as well as chub mackerel) tended to have aggregate catches that were generally above average prior to 1989 and then below average, with perhaps a return to better catches following the 1998 regime shift. Group 4 species (Pacific sardine, walleye pollock and Pacific herring) tended to increase in abundance (decrease in abundance for Pacific herring) throughout the 1970s and 1980s and then declined (increased for Pacific herring) following the 1989 regime shift. Three fisheries, Pacific ocean perch, sablefish and Pacific saury, did not appear to fit in any of the other groups. Pacific ocean perch and sablefish were the longest lived species considered in the study, and perhaps the large number of year classes supporting the fishery and the more conservative approach to management of these long-lived species masks changes associated with climate change. It is clear that climate or ocean conditions can, and do, influence recruitment dramatically but there does not appear to be a strong climate signal detectable in the annual catch time series. Pacific saury have one of the shortest life spans for the species examined in this study and there may be too much variation in the catch data to detect a climate signal, but one may still be present.

Conclusion

There is evidence that climate trends affect the production of the species that make up the major fisheries of Canada, Japan, People's Republic of China, Republic of Korea, Russia and the United States of America. There also is evidence that the dynamics of major fisheries can be associated with trends in climate. The type of climate that affects a particular species can vary depending on the mode of variability that is important to the life history of the particular species. Recognizing that species evolve to adapt to environmental pressures, it should be expected that different types of climate variability will be important. It is noteworthy that climate effect frequently occurs in trends. Unfortunately, the mechanisms linking climate trends to production are poorly understood. Equally unfortunate is our inability to forecast how global warming will affect the dynamics of our key climate indicators, such as the winter intensity of the Aleutian Low. Hindsight shows us that major fluctuations in the abundances of key species and their fisheries will occur in the future. These fluctuations might be better anticipated today than 30 years ago, but we still lack an ability to forecast changes in trends that are useful to management. A common factor affecting recruitment in all reports was the ocean conditions in the spawning and rearing area that affected the amount of prey available to first-feeding young. The key to discovering the mechanisms may be to conduct research before, during and after the events that cause a cycle of production to shift. Such research could be facilitated if the mechanism that shifts regimes could be determined. Accordingly, researching the physics of regime shifts is considered important.

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Country Reports

Canada

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The Fishery

Total fishery landings of all marine fish off the west coast of Canada (Fig. 3) increased during the 1980s, reaching a maximum of 417,777 t in 1994, and declined through to the present, approaching landings common in the early 1980s (Fig. 4). The commercial fishery off Canada's west coast has been strongly influenced by the size and value of the wild Pacific salmon (*Oncorhynchus* spp.) fishery. Catches of all species of Pacific salmon reached historic high levels by the late 1980s (Fig. 5; Beamish and Noakes, 2004), followed by a precipitous decline to historic low levels from the late 1990s to the present.

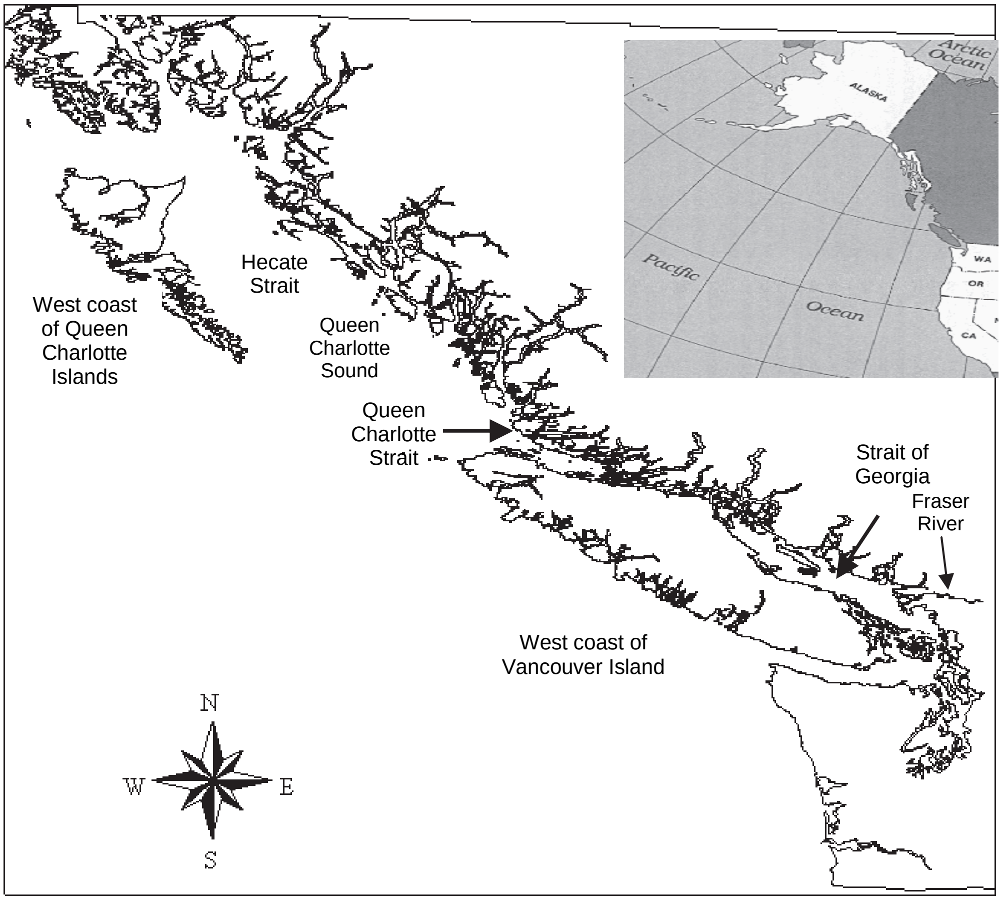

Fig. 3 Map of the west coast of Canada.

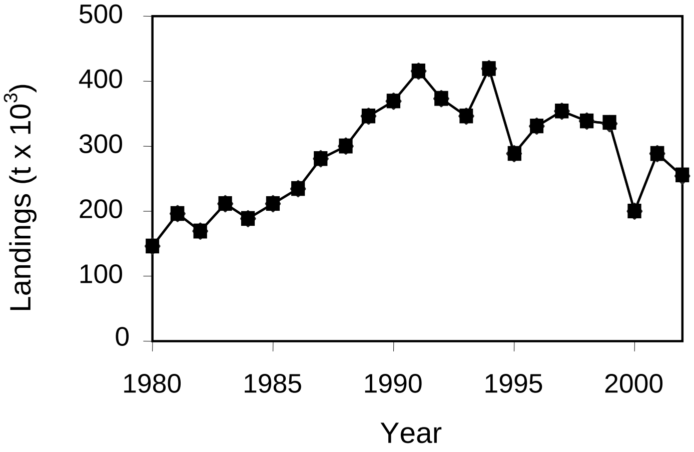

Fig. 4 Total landings of all marine fish off the west coast of Canada from 1980 to 2002. The FAO data base was used and catches of Pacific hake and Pacific sardine by Canadian fisheries were added.

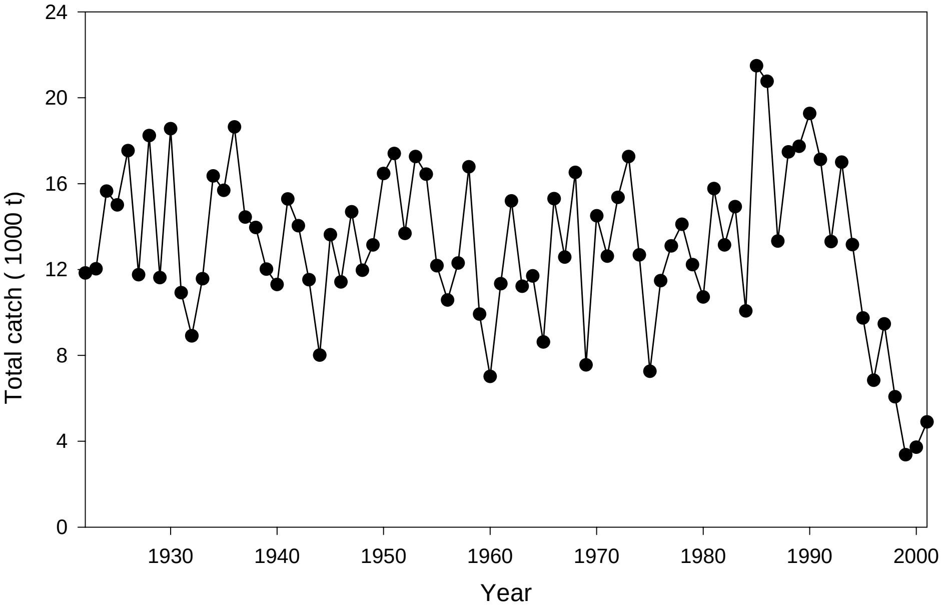

Fig. 5 Total annual Canadian catch of all species of Pacific salmon from 1922 to 2001.

The increase to the historic high levels and the rapid decline to historic low levels was a result of climate changes and management (Beamish *et al.*, 2000; Beamish and Noakes, 2004). The increases in the 1980s occurred because marine survival improved after the 1977 regime shift (Beamish and Bouillon, 1993) and management actions adapted to the improved ocean productivity by increasing escapements and protecting freshwater spawning habitat. However, another regime shift occurred in 1989 (Hare and Mantua, 2000; McFarlane *et al.*, 2000), which generally reduced the marine survival rate, and productivity of Pacific salmon that went to sea in the early 1990s (Beamish *et al.*, 2004a). It is possible that some overfishing occurred in the early 1990s, particularly for coho salmon (*O. kisutch*) and perhaps chinook salmon (*O. tshawytscha*), exacerbating the effects of the reduced marine productivity. As a result, the total returns of some stocks and some stock aggregates became so small that fisheries had to be reduced or shut down completely. Consequently, the total catches declined in part because of the reduced abundance, and in part because fisheries were closed or reduced. The decline in total catch in 2001 compared to the total Pacific salmon catch in 1985 was approximately 90,000 t, which was about 1.5 times greater than the average total catch of 60,000 t of all species of Pacific salmon in British Columbia from 1922 through to 2000.

The decline in Pacific salmon catch and the subsequent management decisions to close fisheries also appear to be related to economic conditions (Noakes *et al.*, 2002). There was a steady increase in the production of farmed salmon in British Columbia and in the world that paralleled the decline in the abundance of wild Pacific salmon in British Columbia. In British Columbia, the production of farmed salmon, which is primarily Atlantic salmon (*Salmo salar*), increased from 0.12 t in 1985 to 67.7 t in 2001 (Fig. 6A and B).

Another major change in ocean conditions occurred in 1998 (Fig. 7). This change was associated with improved marine survival of Pacific salmon in British Columbia (Beamish *et al.*, 2001; Beamish and Noakes, 2004; Beamish *et al.*, 2004a). The abundance of a number of species increased and in some cases, such as pink salmon (*O. gorbuscha*) produced in the Fraser River, the returns in 2001 and 2003 were at historic high levels (Beamish and Noakes, 2004). However, despite these increases in abundance, new considerations in management and reduced value of wild salmon continue to influence the size of catches.

The total landed value of all British Columbia fisheries, including farmed salmon, has been virtually constant at an average value of about CAD (Canadian) $600 million since 1993 (Fig. 8). The total catch of all species, including farmed salmon production, has declined slightly since the early 1990s (Fig. 9).

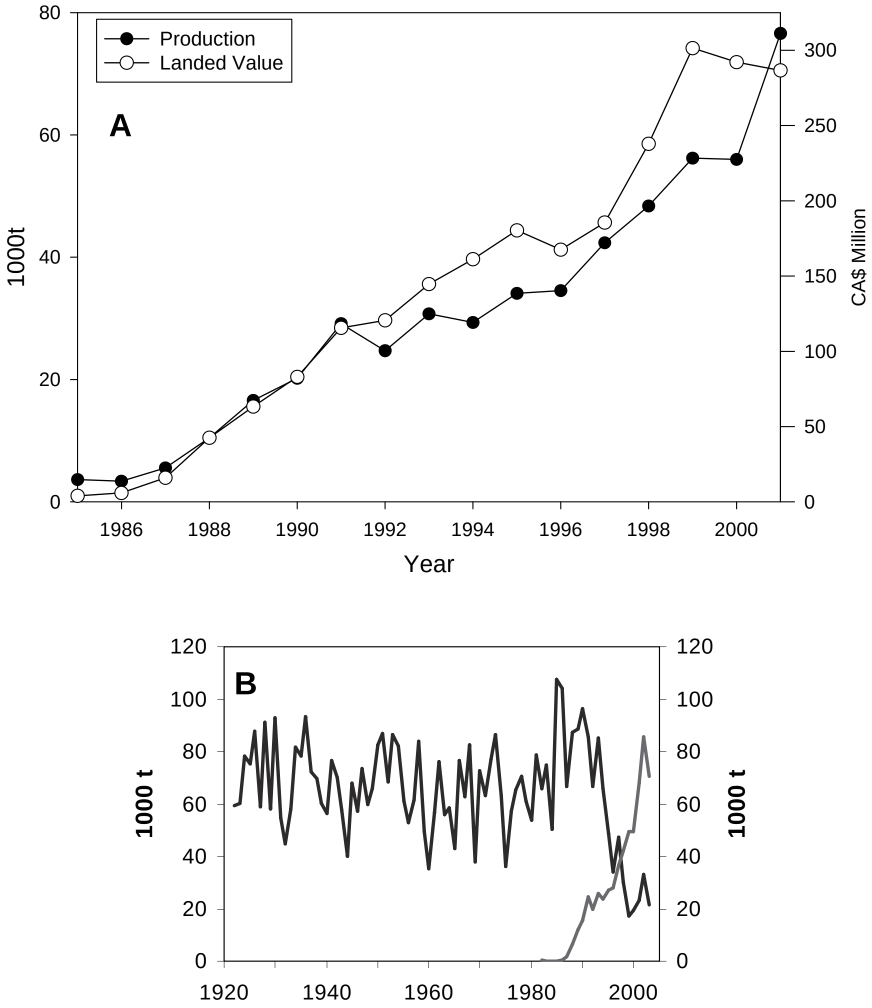

Fig. 6 (A) British Columbia aquaculture production and value from 1985 to 2001 (BCMAFF, 2002). (B) Total catch of wild Pacific salmon, as shown in Figure 5, (dark line) and the production of farmed salmon, beginning in the 1980s (grey line).

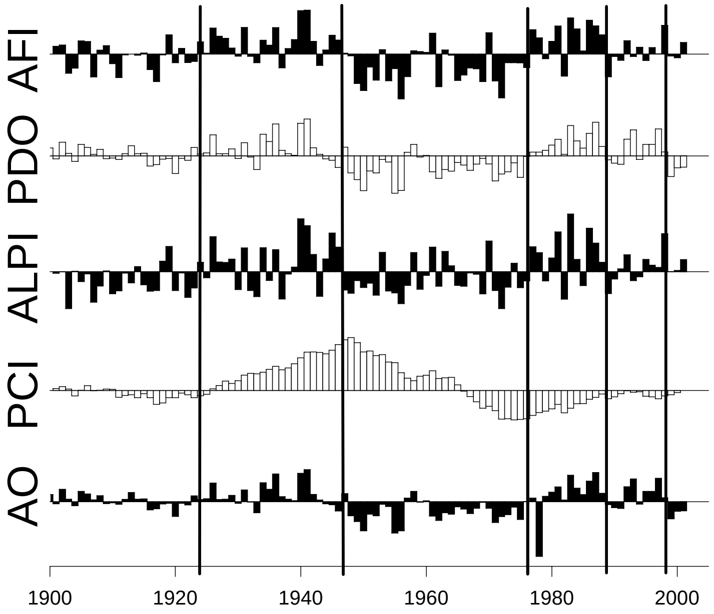

Fig. 7 Indices of climate change: the Atmospheric Forcing Index (AFI), Pacific Decadal Oscillation (PDO), Aleutian Low Pressure Index (ALPI), Pacific Circulation Index (PCI), and Arctic Oscillation (AO). Vertical lines denote timing of regime shifts.

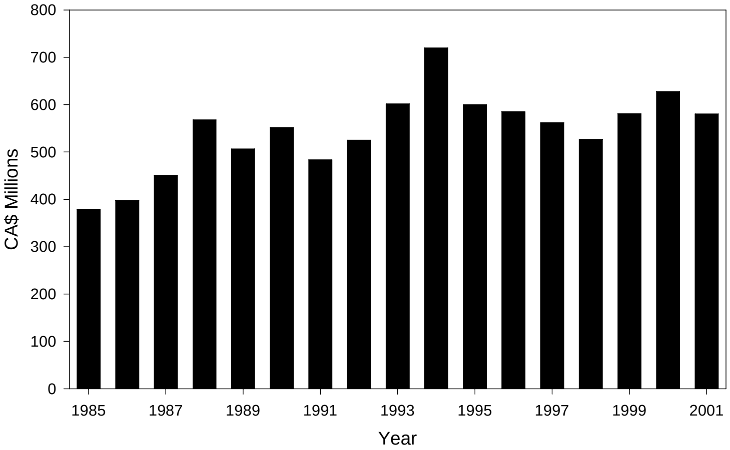

Fig. 8 Total value of fisheries landings in British Columbia (BCMAFF, 2002; Department of Fisheries and Oceans (DFO) commercial catch statistics Information Management Division, Pacific Region Data Unit).

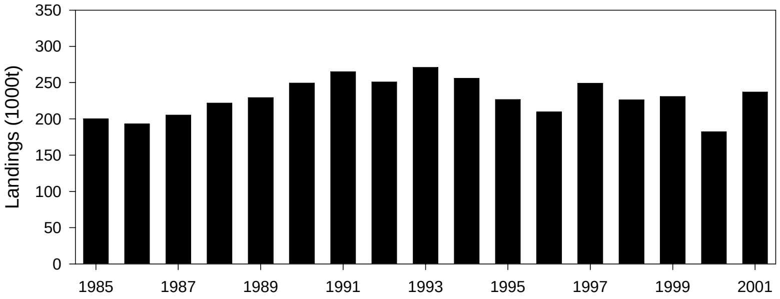

Fig. 9 Total commercial fishery landings plus aquaculture production in British Columbia from 1985 to 2001.

The total landed value of all fisheries, including farmed fish and shellfish, was CAD $580.4 million in 2001. The landed value of wild fish and shellfish was CAD $293.8 million. The landed values have actually increased since the 1980s, in part from the health and wealth associated with the fisheries for Pacific herring (*Clupea pallasii*), Pacific halibut (*Hippoglossus stenolepis*), sablefish (*Anoplopoma fimbria*), and Pacific hake (*Merluccius productus*). There is some discrepancy between the Food and Agriculture Organization (FAO) of the UN and Canada's Department of Fisheries and Oceans (DFO) statistics (Fig. 10A–F), but in general, there has not been extreme year-to-year variability. In fact, catches of Pacific halibut, sablefish and Pacific hake were relatively stable from the late 1980s to the late 1990s.

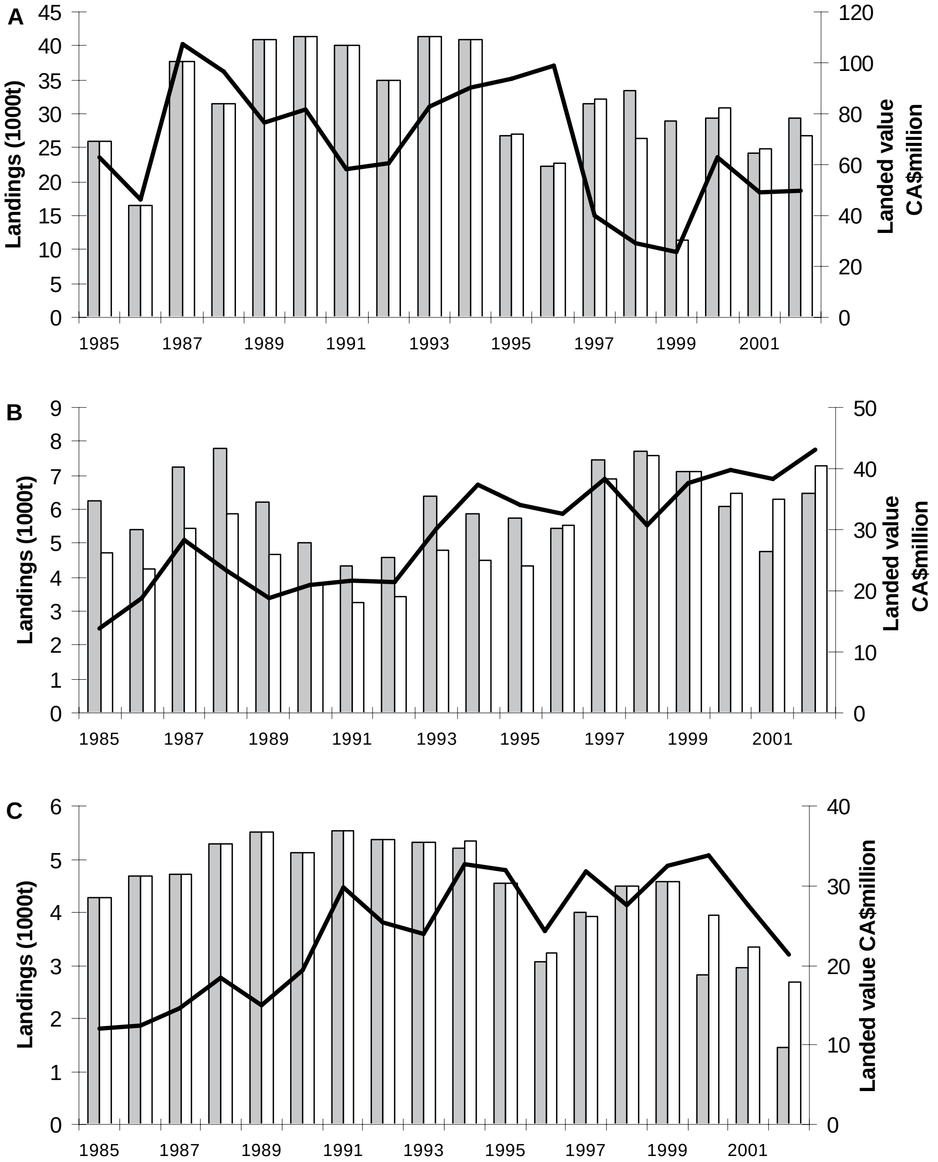

Fig. 10 FAO landings (grey bars), DFO landings (white bars) and landed value (solid line) of (A) Pacific herring, (B) Pacific halibut, (C) sablefish, (D) Pacific hake, (E) Pacific ocean perch, (F) sockeye salmon, (G) chum salmon, (H) pink salmon, and (I) Pacific cod in British Columbia fisheries.

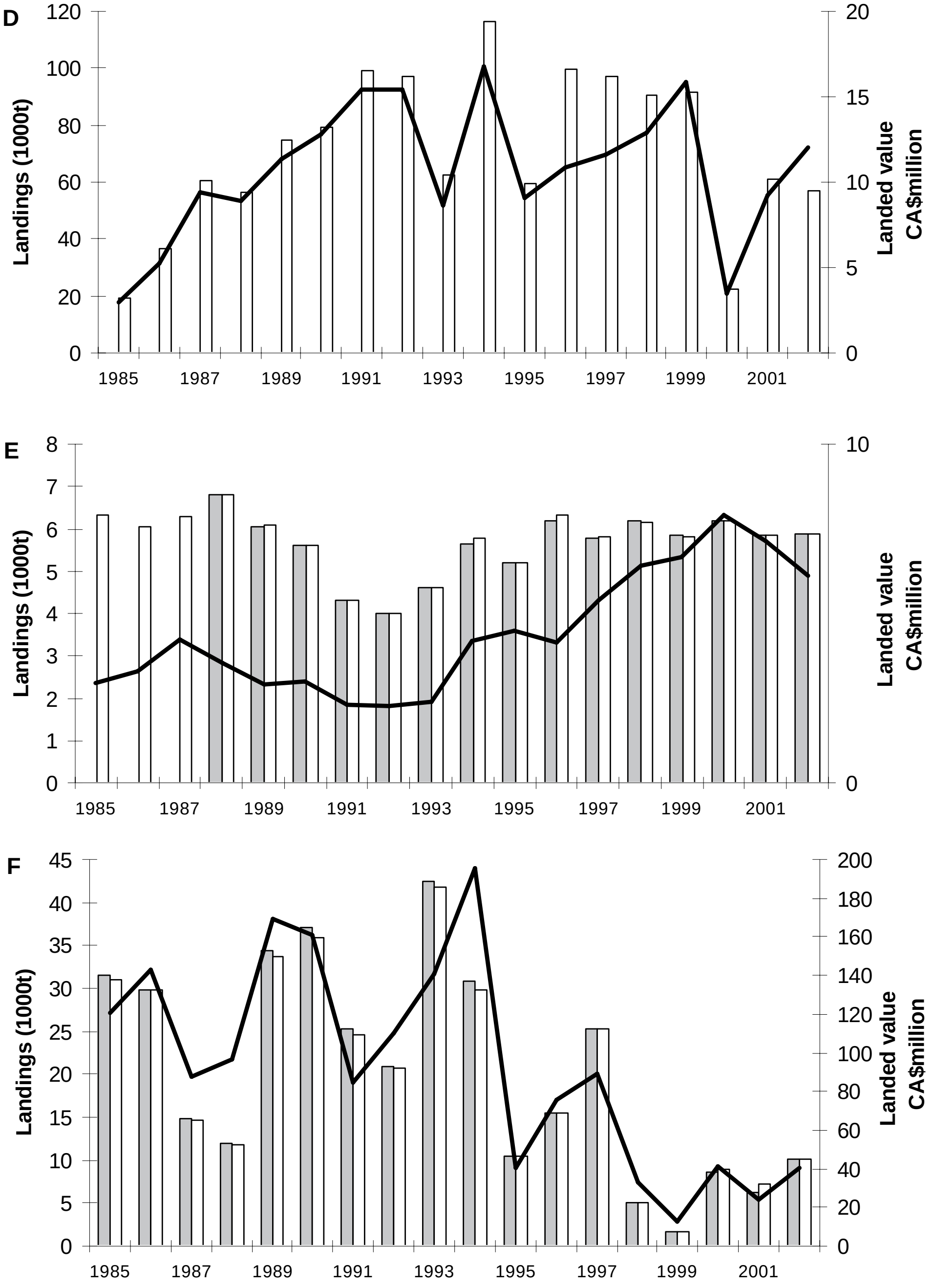

Fig. 10 Continued.

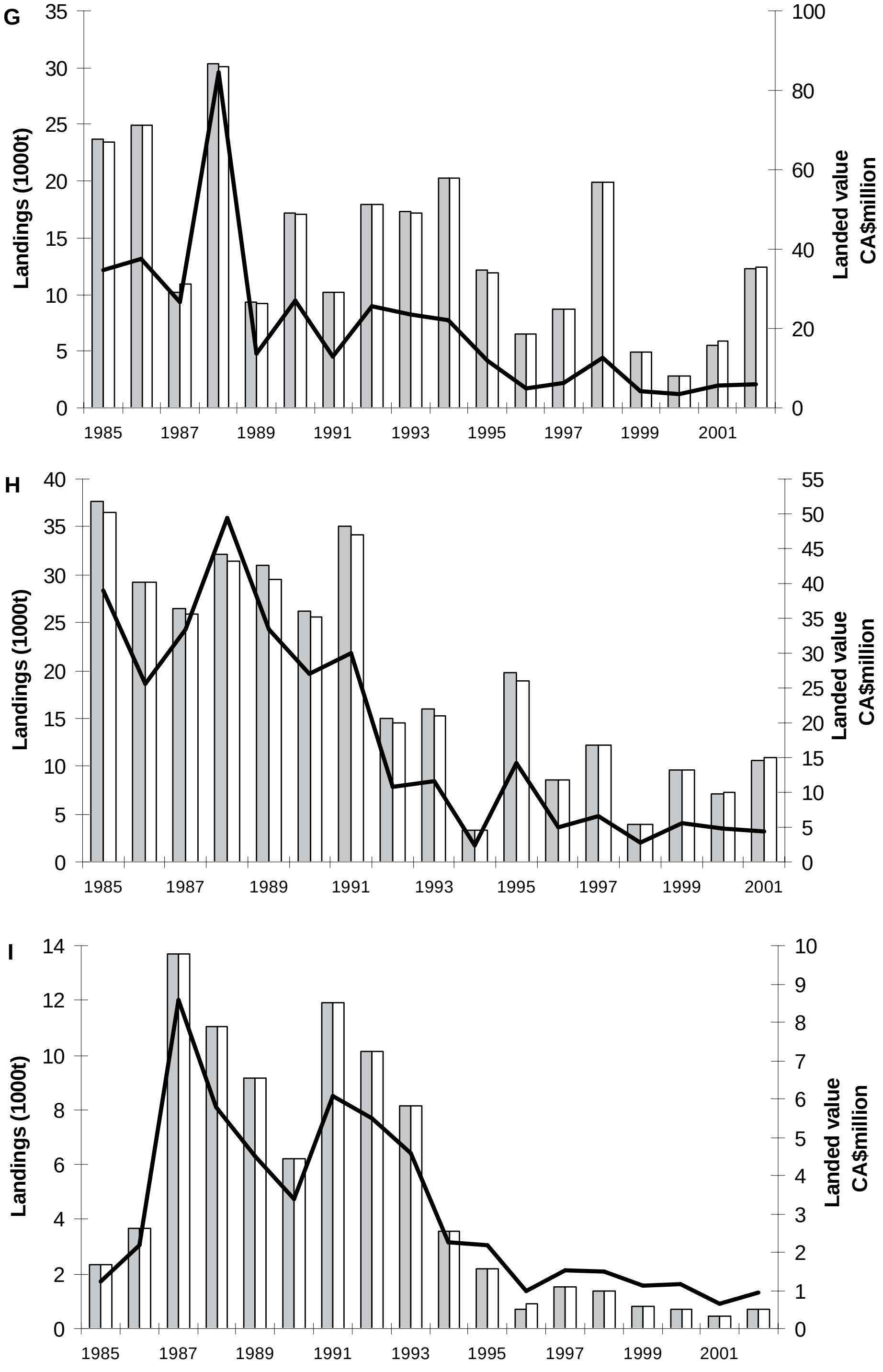

Fig. 10 Continued.

In this report, we focus on ten key species in the fishery off Canada's Pacific coast. These ten species accounted for approximately 43 to 73% of the weight of total landings from 1980 to 2000 (Table 3). Some of these species, such as Pacific halibut, Pacific herring, Pacific sardine (*Sardinops sagax*), and sockeye salmon (*O. nerka*) have been key species in the fishery since the late 1800s. Estimates of production are available for Pacific herring, Pacific halibut, Pacific hake, sablefish, and for pink and sockeye salmon from the Fraser River (Fig. 11). Catch is a good indicator of abundance for Pacific salmon up to the mid-1990s because exploitation rates were high (60–80%) and tended to be constant.

The longevity of a species may be an indication of the environmental impact on reproduction. McFarlane and Beamish (1986) hypothesized that the longevity of a species represents the longest period over evolutionary time that the species survived conditions unsuitable for successful reproduction in the preferred habitat. A species evolves to adapt to extreme climate-related variability in its preferred habitat. In the absence of fishing, the age structure of a population maximizes its ability to survive extremes in the mode of climate variability that most affects its ability to replenish itself.

Short-lived marine species, such as coho salmon and pink salmon, will be the immediate indicators of change and would be expected to have evolved the ability to survive wide fluctuations in their marine habitat at the population level. Pacific cod (*Gadus macrocephalus*) off British Columbia is at the southern limit of its distribution and may also provide an early indication of climate change impacts.

The longevities of fishes in the British Columbia fisheries increase from species that live 3 to 10 years, including Pacific salmon, to species that live 11 to 30 years, such as skate and some sole species through to species that live from 33 to 205 years, including walleye pollock and some rockfish species (Table 4). It would be expected that the strategies evolved to survive the various kinds of natural climate variability in the ocean habitat would differ among these types of fishes. This means that any assessment of climate impact on fish and fisheries must consider the impacts on the life history strategy of the particular species, as well as on its physiology. We propose that a working hypothesis for the impacts of global warming could be that the apparent impact may be related to longevity of a species. Thus, a short-lived species, such as pink salmon, would respond quickly to the impacts and the consequences would be detectable perhaps in a decade. Long-lived species could buffer the impact and it may take many decades to detect the response.

Table 3 Total catches (t) of the key fish species in the British Columbia fisheries (FAO, 2000).

Species	1980	1985	1990	1995	2000
Pacific herring	25,155	25,955	41,280	26,780	29,290
Pacific hake	12,311	14,429	72,866	70,418	22,400
Pacific ocean perch	–	9,043	5,598	5,207	6,177
Pacific halibut	4,396	6,255	5,031	5,745	6,095
Pacific cod	7,817	2,345	6,233	2,172	712
Pacific sardine	–	–	–	25	1,559
Sablefish	2,849	4,263	5,125	4,542	2,811
Sockeye salmon	7,727	31,568	37,134	10,533	8,665
Pink salmon	13,718	37,701	26,240	19,767	7,158
Chum salmon	16,809	23,646	17,181	12,115	2,783
Total	90,782	155,205	216,688	157,279	86,091
Total catch all species	147,108	212,896	370,608	289,782	199,442
% of all species catch	61.7	72.9	58.5	54.3	43.2

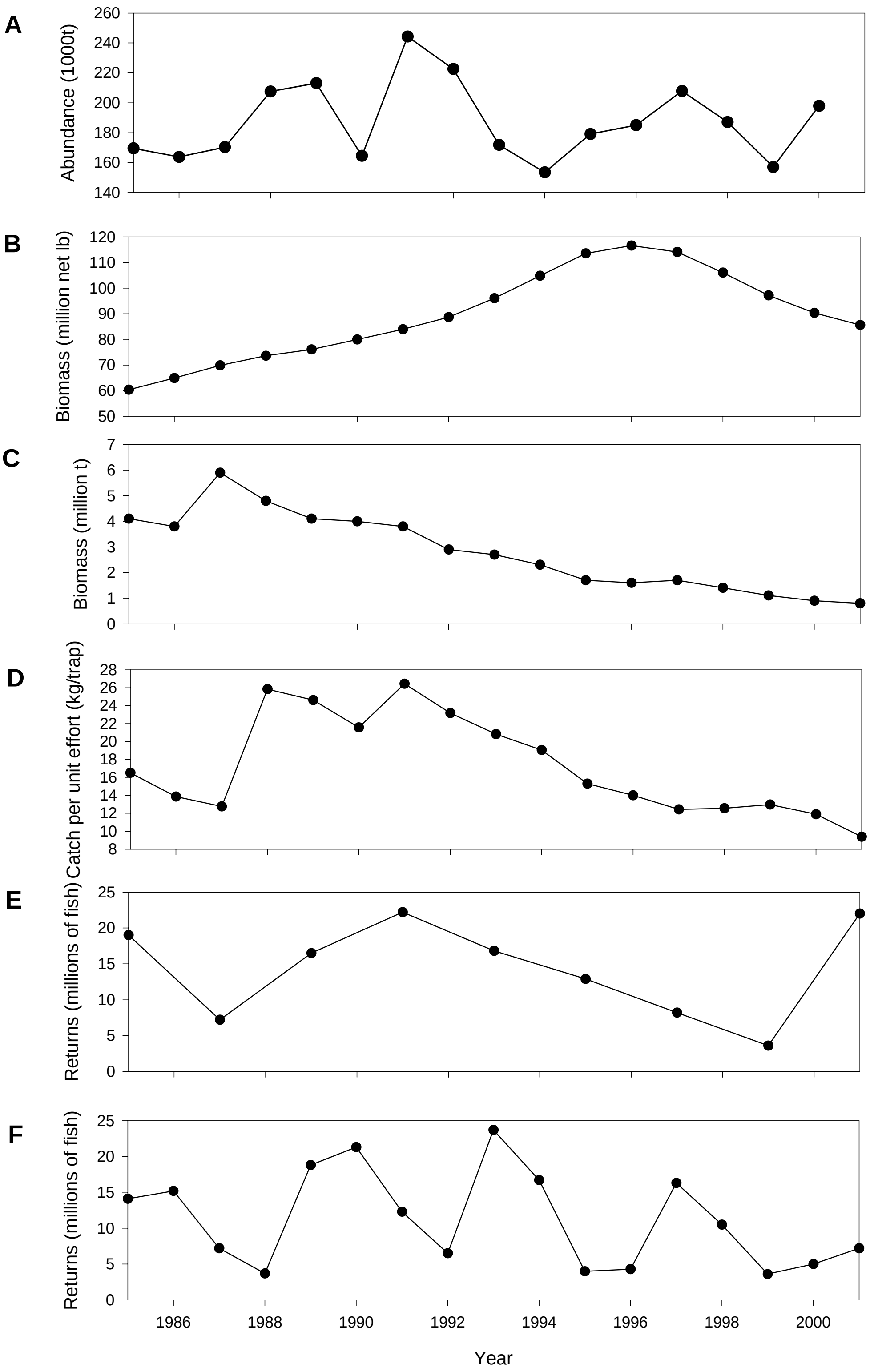

Fig. 11 Production indices of key British Columbia fish species. (A) Pacific herring pre-fishery abundance, (B) Pacific halibut legal sized fish abundance off the west coast of Canada, (C) Pacific hake age 3+ biomass off the west coast of Vancouver Island, (D) sablefish average catch per unit effort, (E) Fraser River pink salmon returns (odd years only), and (F) Fraser River sockeye salmon total production.

Table 4 Total catch and maximum age of finfish off the Canadian west coast (all gear) > 1 t landed in 2000 (King and McFarlane, 2003; Beamish *et al.*, 2006).

Species	Maximum age	Total weight (t)
Rougheye rockfish	205	848
Shortraker rockfish	120	234
Yelloweye rockfish	118	292
Sablefish	113	3947
Pacific ocean perch	100	6179
Yellowmouth rockfish	100	2050
Shortspine thornyhead	100	732
Spiny dogfish	100	244
Redbanded rockfish	93	556
Quillback rockfish	90	197
Rosethorn rockfish	87	17
Splitnose rockfish	86	92
Canary rockfish	84	662
Silvergray rockfish	81	1579
China rockfish	79	30
Tiger rockfish	69	7
Yellowtail rockfish	64	4124
Widow rockfish	60	1971
Vermilion rockfish	60	7
Sharpchin rockfish	58	401
Dover sole	57	3040
Redstripe rockfish	55	1193
Pacific halibut	55	6096
Greenstriped rockfish	54	35
Bocaccio	52	282
Longspine thornyhead	50	723
Copper rockfish	50	48
Black rockfish	50	25
Darkblotched rockfish	48	56
Harlequin rockfish	47	9
Petrale sole	35	405
Walleye pollock	33	1044
Big skate	30	1152
Longnose skate	30	208
Rex sole	27	393
Flathead sole	27	40
Arrowtooth flounder	25	4285
Rock sole	25	1229
Lingcod	25	1984
Pacific cod	25	708
Starry flounder	24	38
English sole	23	710
Pacific hake	23	22347
Slender sole	20	2
Wolf eel	~20	2
Kelp greenling	18	18

Table 4 Continued.

Species	Maximum age	Total weight (t)
Pacific herring	15	27725
Sandpaper skate	~15	4.2
Spotted ratfish	~15	13
Sardine	13	800
Butter sole	11	19
Albacore tuna	10	233
Sand sole	10	19
Curlfin sole	~10	18
Chinook salmon	8	510
Sockeye salmon	7	8670
Chum salmon	7	2780
Coho salmon	4	30
Pink salmon	3	7160

Climate and Ocean Impacts

There are five marine ecosystems off the west coast of British Columbia: (1) the Strait of Georgia, (2) west coast of Vancouver Island, (3) west coast of Queen Charlotte Islands, (4) Queen Charlotte Sound, and (5) Hecate Strait (Fig. 3). There is evidence that a north–south boundary exists and that the climate on either side oscillates as the climate regimes shift. Moore and McKendry (1996) showed that levels of snow pack and large river flows followed opposite trends in the northern and southern areas of the province. Prior to 1977, large river flows and snow pack in the southern part of British Columbia were above average, while flows and snow pack in the northern areas were below average (Moore and McKendry, 1996; Beamish *et al.*, 2000). This pattern reversed after the 1977 regime shift.

There is a minimum in the average sea level pressure off the west coast at about latitude 55°N (Beamish *et al.*, 2000) and it is possible that the oscillation in climate, observed on land, may also occur in ocean ecosystems at approximately 55°N latitude. Hare *et al.* (1999) reported a decadal-scale, north–south oscillation in the catch of coho and chinook salmon, although they did not identify the area where the oscillation was centred.

Beamish *et al.* (2000) looked at the latitudinal position of the lowest pressure from 1965 to the present and found a shift northward in the latitude of the lowest annual sea level pressure beginning in the mid-1970s. In addition to the northward shift of this area of low pressure, there was an increase in the variance of the average sea level pressure (mb) for 50°N between 125°W and 180°W (Beamish *et al.*, 2000). The trends were reversed after the 1977 regime shift. Thus, there is evidence that changing trends in climate may affect the same species differently on the west coast of Canada, depending on its latitudinal distribution.

Hollowed and Wooster (1992) reported shifts in winter sea surface temperatures (SSTs) for the coastal and offshore areas off the coast of British Columbia. Freeland *et al.* (1997) suggested that there is an overall warming trend in SSTs for the British Columbia coastal waters. When the SSTs for an area from 141°W to 123°W and 35°N to 60°N are broken into three regimes (pre-1977, 1977–1989, and post-1989) for winter and annual averages, a difference in warming is detectable. While there was an overall warming trend in winter, exhibited by warmer temperatures for the entire coast in 1989–1996, compared to 1965–1976, the increase in temperature was greater in the regime 1977–1988 than in 1989–1996. These differences in the amount of warming across regimes are not evident in annually averaged data. On an annual basis, there is a continuous increase in temperatures across regimes. Winter is an important period for reproduction of many British Columbia fishes; thus it is important to monitor climate–ocean systems during winter.

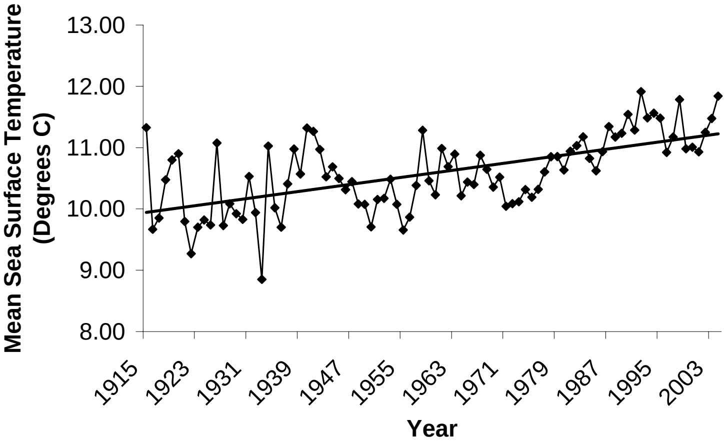

Fig. 12 Mean annual sea surface temperature measured at lighthouses around the Strait of Georgia from 1915 to 2004. A linear trend indicates an increase of 1.0°C over 90 years.

For inshore waters, like the Strait of Georgia, SSTs are measured at lighthouses or are available from temperature profiles. There is a long-term increasing trend in SSTs of 1.0°C from 1915 to 2004 (Fig. 12). Within the Strait of Georgia, SSTs from lighthouses were below average prior to 1977, were just above average from 1977 to about 1988, and in the 1990s continued to increase. SSTs measured just offshore from Nanoose Bay in the Strait of Georgia also exhibited a similar pattern. Bottom temperatures at this site have shown an overall warming, with the switch from below average to above average temperatures occurring in the late 1970s. It is important to note that the regional indicators of decadal-scale changes measure similar ocean–climate systems as do the basin-scale indicators. Changes in the large-scale climate and ocean indicators, therefore, would be expected to be reflected in the dynamics of the coastal oceanography off British Columbia. Beamish *et al.* (2000) reported that the winter (December through March) atmospheric patterns over British Columbia generally match those for the Pacific region. Prior to 1977, the winter frequencies of westerly and northwesterly circulations were above average. Since 1977, southwesterly circulation was above average until about 1991, when westerly or northwesterly circulation was again above average. The regime from 1977–1988 could be classified as a period of extreme low pressures and extreme variation. The post-1988 regime was characterized by a return to higher average annual pressures. There are studies that report north–south differences in Pacific salmon catch (Hare *et al.*, 1999) and ocean processes (Gargett, 1997). It is likely that these north–south differences are related to the changing pressure trends around 55°N.

Large rivers are important influences in the productivity of coastal areas in British Columbia. River flows into areas such as the Strait of Georgia have a significant impact on the estuarine circulation, and consequently on primary productivity. The largest rivers in British Columbia are also the important spawning areas for Pacific salmon. The Skeena, Nass and Fraser rivers originate from mountain snow packs and all produce large numbers of salmon. The maximum discharge from these rivers occurs about June, whereas smaller, more coastal rivers that receive most of their water from winter rains have their maximum discharge in the winter. Flow data are available for these smaller rivers, but the time series are too limited to allow for any kind of province-wide study. The average annual pattern of discharge from the Skeena, Nass and Fraser rivers shows distinct changes around 1977 (Beamish *et al.*, 2000). The northern rivers, the Skeena and Nass, both exhibited a decreasing trend in discharge from the late-1950s to 1976, and an increasing trend from 1977 to 1989. The increases in discharge post-1976 corresponded to the heavier than average snow pack observed in northern British Columbia by Moore and McKendry (1996). The Fraser River exhibited an increase in discharge from 1945 to 1976 and a decreasing trend from 1977 to 1989, which again corresponds to snow pack variation observed by Moore and McKendry (1996). Even with the opposite linear trends in the northern and southern rivers, in the regime prior to 1977, extreme high and low discharge years were virtually identical in all three rivers and fluctuations were more frequent and extreme. After 1977, the inter-annual fluctuations were less extreme and the extreme years in the south no longer matched those in the north.

Although there has not been a clear change in the total annual discharge for the Fraser River after the 1989 regime shift, there has been a clear change in the timing of the onset of the spring flows. The April discharges have dramatically increased since 1989 and were higher than all previous April flows. This indicates an earlier start of the spring freshet that eventually leads to the maximum discharge in June. As the Fraser River discharge is closely related to the oceanography of the Strait of Georgia via estuarine circulation (Thomson, 1981), it would be expected that changes in discharge would have impacts on the dynamics of this marine ecosystem.

Potential Impacts of Global Warming on the Climate and Ocean Environment of Key Species in the Fishery

In Canada, numerous senior government officials, business leaders, scientists and concerned citizens have characterized human-induced climate change as the greatest environmental and economic challenge of this century. In fisheries science, there now is solid evidence that climate change profoundly impacts the population dynamics of important species. No longer do scientists believe that abundance fluctuations are primarily a result of fishing effects. There is also compelling evidence that the climate in the past is an unreliable predictor of the future. This new understanding of the importance of including climate in fisheries management, along with the observation that the relationships of the past may not be guides for the future could be viewed as creating a crisis in fisheries management. Certainly, it is clear that we need to assess how the past dynamics of a species can be used to forecast future dynamics. If the past cannot be used as a guide to the future, there will be little choice but to reduce fishing in the face of uncertainty.

The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001a) provided a series of scenarios which indicated the kind of changes that will occur to future climates. The extent of changes depends primarily on the level of emissions of CO_2. For example, if there are no changes in the current rate of increase of CO_2, then the global average surface air temperature is predicted to increase by 3°C by the 2080s compared to the present. The land areas will warm twice as fast as the oceans, with more warming occurring in the winter in high latitudes. If CO_2 emissions can be controlled and stabilized at two times the pre-industrial levels (*i.e.*, 550 ppm), or three times the pre-industrial levels (*i.e.*, 750 ppm), then the impacts will be different. A rise of 2°C about the present day, which is expected by the 2050s, would be delayed by 50 years if CO_2 emissions were stabilized at 750 ppm and by over 100 years if stabilization occurred at 550 ppm (IPCC, 2001b). If current CO_2 emissions were reduced by 60 to 70%, there would still be a 0.7°C increase in global average surface temperatures. This is approximately the magnitude of change observed over the last 150 years. Associated with this general warming in the past 150 years, there has been a gradual decrease in the number of cold days and an increase in the number of warm days. In northern latitudes, winters have been wetter and summers drier. The 1990s were particularly warm, with 1998 being the warmest year since instrumental records began in the mid-1800s.

A standard reference point used to provide a scale of possible change is 2°C by the 2050s if there is no change in the rate of CO_2 production (if CO_2 is stabilized at 550 ppm, the 2°C increase would occur about 2230). Sea level rise is mainly associated with the thermal expansion of water and water from melting glaciers and ice caps. This sea level rise is an inevitable consequence of global temperature increase. The projected rise between 1990 and 2100 is between 9 and 8.8 cm. The central value is 4.8 cm, which corresponds to an average rate of about two to four times the rate observed during the 20th century. An estimate of a 40 cm increase in sea levels by the 2080s would be delayed by about 25 to 40 years if CO_2 emissions were stabilized at 750 or 550 ppm, respectively. The variation in the range of sea level rise at the regional level could be substantial. It is likely that precipitation will increase in the northern mid-latitudes in the winter and in the northern high latitudes in the summer and winter. There is an expectation that the increases in precipitation will also result in increases in extreme precipitation events. Relative to the 1961 to 1990 average, the expected increases of 20 to 40% appear modest, but there is not good agreement among models.

The variables associated with global warming that affect fish production are temperature, precipitation, winds, currents, sea level, salinity, upwelling, ice coverage, and UV-B radiation. In the Third Assessment Report of the IPCC (IPCC, 2001a), there is better agreement among models about changes in temperature and sea level than about precipitation, winds, and storminess. Temperature is important, but winds and storminess may be the parameters that most affect ecosystems in the subarctic Pacific. The assessment of the impact of climate change on marine fishes in the third IPCC assessment report emphasized the impacts on the ecosystems that support the particular species of interest (IPCC, 2001a). The importance of temperature, salinity, nutrients, sea level, currents, and the amount of sea ice were noted, as all of these abiotic factors will be affected by climate change. However, there was much greater emphasis on the impacts of the carrying capacity of ocean habitats than in the past. The response of individual species to temperature change has been the focus for impacts because we know much more about temperature responses than the factors that affect carrying capacity. There are examples in the Third Assessment Report of how temperature increases will affect abundances and distributions, have an impact on spawning success, affect larval and juvenile survival, affect growth, and the rate of food production which, in turn, affects food availability for a species. However, scientists are increasingly recognizing that there are natural long-term fluctuations in fish production that occur over scales of 10 to 60 years. These natural cycles emphasize the importance of considering the ecosystem impacts of climate variations, as well as changes to individual species. The Third Assessment Report emphasizes that the assumptions that marine ecosystems are stable are no longer acceptable. In fact, some scientists are proposing that the success of future fish stock assessments and the success in sustaining world fisheries would depend to a large extent on the ability to predict the impacts of climate change on the dynamics of marine ecosystems. A complication in the understanding of climate impacts on ecosystems is the recent discovery that changes in ecosystem dynamics may occur quickly and persist in a new organization on a decadal scale.

Decadal-scale variability is now a generally accepted phenomenon within the fisheries science community (Beamish *et al.*, 1999; Hare and Mantua, 2000; Benson and Trites, 2002). Large-scale climate oscillations have been described for the Arctic (Thompson and Wallace, 1998), the Atlantic (Hurrell, 1995), and the Pacific (Beamish *et al.*, 2000; Hare and Mantua, 2000; McFarlane *et al.*, 2000). General trends in atmospheric circulation patterns that change quickly to new states have also been described for areas over Europe and over the subarctic Pacific (King *et al.*, 1998; Beamish *et al.*, 1999). The North Atlantic Oscillation has recently been shown to be related to a variety of marine ecosystem changes, and new regime-related explanations for old events are routinely being described. The large inter-decadal climate fluctuations that occurred in the North Pacific have not yet been reproduced effectively in climate models; however, they are a critical component of the variability. In the Pacific, decadal-scale variability results in abrupt changes in the dynamics of mid-ocean and coastal ecosystems (Deser *et al.*, 1996). Coupled global climate models or atmosphere–ocean general circulation models will have to be able to simulate the regime shifts before it will be possible to predict the changes to the dynamics of the fish populations in these ecosystems. One attempt to assess the decadal-scale changes by Mote *et al.* (1999) indicated that both the UK Hadley Centre and Canadian Climate Centre models predicted an increase in the intensity of the Aleutian Low pressure area in the winter in the subarctic Pacific. One model indicated a general trend towards stormier winters, while the other model indicated a greater variability followed by an increased trend to stormier winters. Increased storminess has been associated with increased production in the open ocean, but the impacts of a combination of warmer oceans and increased storminess remain to be determined.

Because decadal-scale variability can be large, and the causes are not known, it is possible that one of the most important impacts of global warming will be the change in the nature of decadal-scale variability. More frequent changes and more extreme changes will have profound impacts on ocean currents, followed by impacts on the dynamics of fish, fisheries, and fisheries management. Evidence for such impacts can be found in the effects observed in the 1990s for species such as coho (Beamish *et al.*, 2000). The magnitude and abruptness of such changes may become the major factor in the regulation and management of marine fisheries.

The impacts of decadal-scale changes in climate that may be superimposed on a gradual warming trend are difficult to forecast. We know that after the 1977 regime shift there was an abrupt increase in sea surface temperatures that was maintained. A good example of this change was observed in the Strait of Georgia (Beamish *et al.*, 2002; Fig. 13). There was an abrupt increase in sea surface temperatures in 1977, followed by another increase after the 1989 shift. In recent years, there has been a cooling following the 1998 regime shift. The cause of these climate shifts is not known. Changes in river discharge can be harmful to Pacific salmon that must migrate up the Fraser River in the summer during peak discharge (Morrison *et al.*, 2002). Morrison *et al.* estimated that greenhouse gas-induced climate change would cause a modest 5% increase in average flow over the years 2070 to 2099. However, they found that the peak flow would decrease by 18%, and on average would occur 24 days earlier. We suggest that regime shift impacts would exacerbate the impacts of changes in flows combined with temperature increases of 1.9°C (Morrison *et al.*, 2002). The additional energy required to migrate to spawning areas may stress Pacific salmon, making them susceptible to disease and other sources of mortality.

There is a north–south coastal oscillation in Pacific salmon production (Hare *et al.*, 1999). Chinook and coho salmon have higher marine survivals in the north during intense Aleutian Lows than in the south. Another mode of climate variability that has been reported to affect Pacific salmon and other west coast marine species is El Niño–Southern Oscillation (ENSO). State-of-the-art Global Climate Change Models are increasingly improving their ability to model ENSO changes in relation to greenhouse gas accumulations. Recent scenarios appear to be predicting more frequent El Niños or perhaps longer El Niño-like states (Timmerman *et al.*, 1999). It is critical that we understand how these modes of variability will change because we need to consider how the less variable changes in temperature or precipitation will impact on the biological processes that characterize the particular species.

Model predictions for coastal British Columbia indicate that for a doubling of CO_2, average surface temperature increases would range between 2° and 4°C. Precipitation increases would be greater in the south in the winter, perhaps a 30 to 40% increase, compared to a 10 to 20% increase in the north. In general, changes for British Columbia that can be inferred from recent model outputs for a doubling of the CO_2 scenario are that there would be an average temperature increase of about 2.9°C and a decrease (1.1 cm) in precipitation in the summer and an increase (3.4 cm) in the winter. There seems to be better agreement that the winters will be warmer and wetter, but there is less agreement about whether the summers will be wetter or drier (Mote *et al.*, 1999).

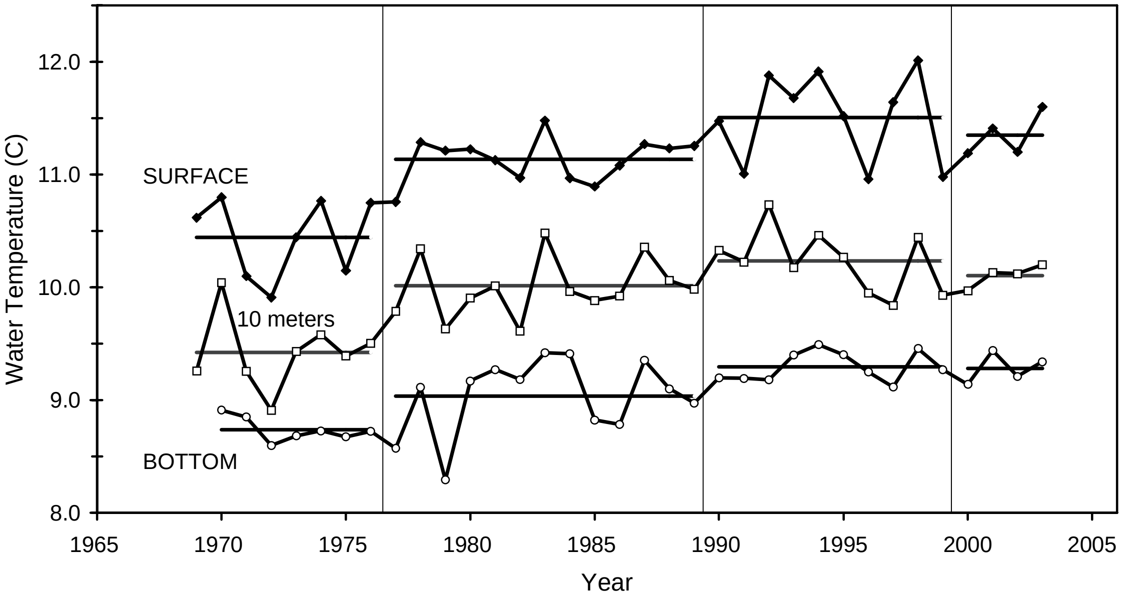

Fig. 13 Water temperatures at the surface, 10 m, and bottom in the Strait of Georgia from 1965 to 2001.

Beamish *et al.* (1997a) acknowledged that there is considerable uncertainty about the physical changes that will occur in the ocean habitat of key species in the marine fisheries of British Columbia. IPCC (1990) calculated that the warming would increase biological productivity in the coastal areas off the west coast of North America. Hsieh and Boer (1992) proposed that the opposite would happen. Beamish *et al.* (2002) suggested that the modelled scenarios of Mote *et al.* (1999) might mean that there would be a tendency for stormier winters and thus more conditions similar to those of the 1977 to 1989 regime. Welch *et al.* (1998) proposed that sea surface temperatures had an overriding influence on the distribution of sockeye salmon resulting in a more northerly distribution. Beamish *et al.* (1997b) reported that other factors in addition to temperature affect the relative abundance and distribution of fishes. There is a carrying capacity for the various species in aquatic systems that are a function of the biology of the species and its interrelationships with its environment and associated species. Specific factors that regulate the carrying capacity are poorly known for virtually all species, but we do know that there is some stability in the relationships among species, as large fluctuations in abundances are not common.

A summary of the potential global warming impacts is presented in Table 5. At the end of this report, we will discuss how these potential changes will affect the population dynamics of key species in the fishery that are described in the following section.

Table 5 Summary of potential changes and impacts of climate change by the year 2050.

Change	Impact
Increase in air and ocean temperatures of 1º to 2ºC	Freshwater temperature increases will affect Pacific salmon survival. Ocean temperature changes will affect growth, juvenile survival and distributions of some species, such as Pacific salmon, Pacific cod and Pacific hake.
Increased intensity of the Aleutian Low and more and longer periods of a positive Pacific Decadal Oscillation	Greater variability in primary production with a trend to improved abundance of long-lived species as a result of more frequent stronger year classes.
More frequent north–south oscillations in coastal productivity	In association with coastal warming, species off Vancouver Island will have reduced long-term production, while species in the north will have increasing trends in production.
Increased coastal precipitation and reduced coastal salinity	River flows will be reduced in the summer and will be higher in the winter. The lower flows and warmer temperatures will increase pre-spawning mortality of Pacific salmon.

Key Species in the Fishery

Sablefish (*Anoplopoma fimbria*)

Biology

Sablefish are distributed from northern Mexico to the Gulf of Alaska and Aleutian Islands, along the edge of the continental shelf in the Bering Sea to the coasts of Siberia, Kamchatka and northern Japan. In Canada, most juvenile sablefish inhabit the shallow waters of Hecate Strait and the west coast of Vancouver Island, and move to slope waters off northern and southern British Columbia as they mature.

It is believed that there are two sablefish populations of the west coast of North America, separated at approximately 50°N into an Alaskan population and a west coast population. There is debate about the degree of movement between these two populations. Recent information using stable isotopes found in otoliths indicates that a third population may exist at the southern limit of the distribution. Adult sablefish are abundant in coastal British Columbia waters at depths greater than 200 m, and are most abundant between 600 and 800 m. Spawning occurs from January to March along the entire Pacific coast, at depths of about 300 to 500 m, with no appreciable latitudinal spawning migration. Larval fish hatch at about 300 to 400 m, and then descend to 1000 m by 18 days after spawning. Within a few days of their descent, larval sablefish begin to ascend and feed on copepod larvae. Recruitment appears to be determined at the larval stage. Juveniles are found in shallow (< 200 m) inshore waters and rear in nearshore and shelf habitats until age 2 to 5. As sablefish mature, they move back into the deeper water where spawning occurred.

Growth of young sablefish is rapid in the first few years, and then slows appreciably in this long-lived species. Length and age at 50% maturity are 58 cm, age 5 for females, and 53 cm, age 5 for males. Males tend to undergo a reduction in growth rate earlier than females. The majority of fish in the fishery are between the ages of 4 and 35, but the oldest sablefish aged to date is 113 years. In Canadian waters important prey items for sablefish include rockfish, Pacific herring and squid.

Fishery

The sablefish fishery is one of the few and oldest deep water fisheries of the world. The fishery was reported to be as large as about 6000 t in the 1910s. This early fishery provided a smoked or salted meat product as well as livers for vitamin A and D production. The fishery was encouraged as a way to adapt to a shortage of meat during the First World War (Ketchen and Forrester, 1954). Catches declined into the 1920s, possibly because of a reduced demand after the war. It was not until the late 1960s that catches of sablefish increased as a consequence of a Japanese fishery established outside of Canada's exclusive fishing zone. Following the extension of the exclusive fishing zone in 1977, the fishery was exclusively Canadian and accounted for annual catches ranging from 830 t in 1978 to 5,381 t in 1989. The average commercial landings from 1978 to 2002 were 4,071 t (Fig. 11). Sablefish landings fluctuated in the 1990s, with declines in recent years (Fig. 10C). The declines in catch are related to stock assessments that recognize a decline in biomass as indicated by the declining trend in catch per unit effort (Fig. 11D). Since 1973 the dominant fishing gear used by the fishery has been Korean conical traps (73% of the annual landings). In 1990, the fishery switched to an individual quota for each vessel in an attempt to stabilize the length of the fishing season, improve management, optimize the landed value, and reduce quota over-runs.

Climate and ocean effects

Sablefish exhibit decadal-scale patterns in the relative success of year classes (King *et al.*, 2000). By combining estimates of relative abundance of year classes determined from commercial catches and research surveys for adults and juveniles, McFarlane and Beamish (1992) and King *et al.* (2000) were able to reconstruct an index of year-class success. Year classes from 1960 to 1976 were generally poor with no indication of good year-class success. The 1977 year class was exceptionally large and year classes from 1978 to 1988 were generally average to better than average. Year classes following 1989 and 1990 were generally poor. McFarlane and Beamish (1986) proposed that sablefish live up to > 70 years because their ability to reproduce successfully each year was restricted by their biology and habitat. Their longevity represents the longest period of unsuccessful reproduction over evolutionary time. If this hypothesis is valid, sablefish recruitment is closely related to specific kinds of climate-related ocean conditions. One limiting factor would be the ability of the fragile eggs to remain suspended in mid-depths and for the larval sablefish to find copepod eggs and nauplii immediately after they begin exogenous feeding. It was observed that despite high fecundity, strong year classes resulted from both large and small spawning biomass (McFarlane and Beamish, 1986). It was also observed that the production of strong year classes was closely associated with copepod production at a site off the west coast of Vancouver Island (McFarlane and Beamish, 1992). The periods of above average year-class strength coincided with stronger Aleutian Lows, more frequent southwesterly winds, below average temperatures in the subarctic Pacific and warmer sea surface temperatures off the west coast of British Columbia (King *et al.*, 2000). In general, the pattern of year-class success matches the patterns of regimes and regime shifts. This is evidence that there are trends in sablefish production that are related to climate and ocean conditions on a decadal scale. The recent declines in biomass (Fig. 11D) reflect fishing removal and declining recruitment, which is related to the generally less productive regime in the 1990s.

Pacific herring (*Clupea pallasii*)

Biology

Pacific herring have traditionally been one of the major fisheries off Canada's west coast. They are pelagic, occurring both inshore and offshore from California to the Beaufort Sea. In British Columbia they enter the current fishery at age 2+ or in their third year of life. Few live past 7 or 8 years, although the maximum age is 15 years. They are sexually mature by age 2 to 5 years. In British Columbia, the fecundity of Pacific herring tends to increase with age and latitude, from about 19,000 eggs for a 2-year-old female, to a maximum of 38,000 eggs for an 8-year-old. The fish migrate into shallow waters in late fall to spawn, and return to deeper waters in late March and early April after spawning. After hatching, larval herring remain in the surface waters, and after a few months they form the large schools typical of adult behaviour. Pacific herring grow rapidly in their first 2 or 3 years until they reach sexual maturity, then growth rates decline.

Fishery

Pacific herring are easily fished when they migrate inshore to spawn in intertidal and subtidal areas. The British Columbia herring population consists of north coast stocks (Queen Charlotte Islands, Prince Rupert and Central Coast), and south coast stocks (Strait of Georgia and west coast of Vancouver Island). The fishery is managed separately for these five areas. The current fishery removes between 30,000 and 40,000 t of adults, but earlier fisheries harvested more than 200,000 t in some years (Hourston and Haegele, 1980). The Pacific herring fishery appears to have started in British Columbia about 1877 (Hourston and Haegele, 1980). After the collapse of the Pacific sardine in the late 1940s, Pacific herring became the major fishery off Canada's Pacific coast, and catches steadily increased to over 200,000 t in the early 1960s. Prior to 1970, Pacific herring were fished to produce fish meal and fish oil. Since 1970 virtually all Pacific herring are fished for roe, which is sold in Japan. The fishery was shut down for a brief period from 1967 to 1970 because of poor stock conditions, but in 1972 a fishery for roe began. Recent catch levels are a consequence of both good stock conditions and a high demand for roe (Fig. 11A). There has been some fluctuation in catch (Fig. 10A) that reflect interannual changes in biomass (Fig. 11A), but in general, herring populations are considered to be healthy. In some areas, in some years, the abundances are low, but in others, such as the Strait of Georgia, the abundances are at historic high levels. Recruitment levels have been estimated as part of annual stock assessments (Schweigert *et al.*, 1998), and these estimates can be used to identify relative year-class strength. The fishery closure from 1967 to 1971 is clear evidence of overfishing in the early 1960s (Hourston and Haegele, 1980).

Climate and ocean effects

Pacific herring have supported a major fishery off British Columbia since the early 1900s. Pacific herring stocks sustained almost 20 years of high catches from the 1940s through to the 1950s. However, there was a change in climate in the 1960s and herring recruitment declined suddenly. Unfortunately, the reduced recruitment was not detected and the population was severely overfished (Hourston and Haegele, 1980). After the fishery was closed in 1967, stocks recovered relatively quickly and fishing commenced in the 1970s. The lesson learned was that climate and ocean conditions can have profound impacts on the recruitment and abundance trends. Another lesson is that Pacific herring appear to be responsive to short-term, climate-related variability. The most important mode of variability for herring may not be the regime scale.

Ware (1991) studied the fluctuations in Pacific herring growth and abundance in southern British Columbia. He concluded that much of the variation in herring recruitment was associated with changes in Pacific hake abundance, zooplankton biomass, and the pattern of moderate and strong ENSO events. A negative correlation between size-at-age and sea surface temperature was believed to be related to fluctuations in plankton biomass that, in turn, were related to natural oscillations in the ocean and climate that occurred at periods of 5 to 16 years. Ware (1991) concluded that the abundance trends of Pacific herring (and other dominant migratory pelagic species) were strongly affected by oscillations in the climate–ocean environment. The timing of the changes in oscillations was observed to be more closely related to ENSO events than to the decadal- or regime-scale changes. However, there was similarity in the timing of the years of regime shifts and the years of change in trends of abundance described by Ware (1991).

In the Strait of Georgia, Beamish and McFarlane (1999) proposed that the key process that regulated herring abundance involved the timing of the vertical migrations and abundance of copepods. McFarlane *et al.* (2000) also reported that Pacific herring survival was higher in the 1990s due to reduced predation by Pacific hake. The availability of copepods to larval herring immediately after yolk sac resorption was proposed as the fundamental mechanism that alters the dynamics of the fish community in the Strait of Georgia. McFarlane *et al.* (2000) explained that the climate impact extended beyond changes in temperature and needed to be studied at the ecosystem level. Copepods are the component of the zooplankton community that links primary production to larval fish survival. Most fish in the North Pacific reproduce in the winter, immediately before juvenile copepods begin to develop from their diapause state in deeper waters to their juvenile stage in the surface waters. It is in the surface waters that the juvenile copepods complete their growth before returning to deep water in the late spring and summer (Miller *et al.*, 1984). Changes in the timing of copepod seasonal migration have been observed for the North Pacific (Mackas *et al.*, 1998; Mackas and Tsuda, 1999), and for the Strait of Georgia (Bornhold *et al.*, 1998), and typically coincide with decadal regime shifts.

Because Pacific herring are dependent on nearshore habitats for spawning, sea level rise and increased storminess would be expected to affect the dynamics of herring populations. Temperature, salinity and ocean circulation patterns are influential in the survival of Pacific herring eggs and larvae (Stocker and Noakes, 1988). On the west coast of Vancouver Island, recent increases in sea surface temperatures have been associated with poor recruitment, but in the Strait of Georgia there was an abrupt shift to warmer temperatures in 1976–1977 and herring abundance increased to levels believed to be close to historic high levels. Warmer surface temperatures off the west coast of Vancouver Island would be expected to be linked to increased Pacific hake abundance in the summer. Increased Pacific hake abundance will result in increased predation in herring and reduced abundances.

Pacific hake (*Merluccius productus*)

Biology

In Canadian waters, there are two distinct populations of Pacific hake: the Strait of Georgia population and the coastal population that occurs off the west coast of Vancouver Island and in Queen Charlotte Sound (Kabata and Whitaker, 1981; McFarlane and Beamish, 1985). The coastal stock ranges from southern California to Queen Charlotte Sound. Since the 1990s the percentage of the stock migrating to Canadian waters has increased, approaching 40% of the total coastal stock, and a range extension to southeast Alaska has been noted. Pacific hake have also been observed spawning off the west coast of Vancouver Island since 1994, although most hake spawn off California. Prior to this, the northernmost limit for hake spawning was thought to be Cape Mendocino, California.

Fish in the coastal population can reach a maximum age of 23 years; however, the majority of hake in Canadian waters are between the ages of 4 and 12. Pacific hake recruit to the Canadian fishery at 5 to 6 years and a fork length of approximately 45 cm. Hake show rapid, relatively constant growth to age 4, followed by little or no growth. Spawning generally occurs at depths up to several hundred meters off south-central California from January to March. In spring, adults migrate north and offshore to feed along the continental shelf and slope. In summer they form large midwater aggregations near the continental shelf break. Generally, it is the older age 5+, larger and predominantly female, hake that migrate in the Canadian zone. Over half of females reach maturity by age 3 and a length of approximately 40 cm. Hake have strong and weak year classes that are almost cyclic in the offshore stock, with strong year classes occurring every 3 to 4 years.

Fishery

Canadian landings of the coastal hake stock averaged 51,000 t annually over the period 1966 to 1989, and 85,000 t from 1990 to 1999. Since then (2000–2002), landings have declined to an average of 43,000 t annually as a result of declining availability in the Canadian zone. The decline in catch (Fig. 10D) resulted from a reduced quota that reflects a gradual decline in biomass (Fig. 11C).

Prior to 1977, the former Soviet Union caught the majority of Pacific hake in the Canadian zone, with Poland and Japan harvesting much smaller amounts. Since declaration of the 200-mile extended fishing zone in 1977, the Canadian fishery has been divided into shore-based, joint-venture, and foreign fisheries. In 1990, the foreign fishery was phased out. Since the demand of Canadian shore-based processors remains below the available yield, the joint-venture fishery continued through 2002. The majority of the shore-based landings of the coastal hake stock are processed into surimi, fillets, or mince by domestic processing plants.

Although significant aggregations of Pacific hake are found as far north as Queen Charlotte Sound, in most years the fishery has been concentrated below 49°N latitude off the south coast of Vancouver Island, where there are sufficient quantities of fish in proximity to processing plants.

The average size of Pacific hake in the Strait of Georgia is smaller than in the coastal population. The size in the fishery declined during the late 1970s and early 1980s from 44 to 43 cm, and decreased again in the 1990s to 36 cm. The average size of age 4 Pacific hake in the Strait of Georgia declined 7% in length and 16.3% in weight from 1979 to 1981 (to approximately 40 cm and 410 g), respectively. In the mid-1990s age 4 hake declined again, 13% in length and 51.2% in weight (to approximately 35 cm and 200 g, respectively). The second decline in size at age occurred at the same time as an increase in numbers of Pacific hake in the Strait of Georgia, as a consequence of strong year classes in the 1990s. There is a small fishery for Pacific hake in the Strait of Georgia, but the small size of the species reduces their commercial importance.

Climate and ocean effects

The coastal migratory stock of Pacific hake is characterized by strong year classes every 3 or 4 years (Dorn and Saunders, 1997). However, recent strong year classes (1990 and perhaps 1994) are not as large as those in the 1970s and 1980s (Dorn and Saunders, 1997). The 1989 climate-related ecosystem changes also had dramatic impacts on the migratory behaviour of the offshore stock. During the 1990s a larger percentage of the migrating stock from California entered the Canadian zone and migrated farther north than in the past into areas off the west coast of the Queen Charlotte Islands and into Hecate Strait (McFarlane *et al.*, 2000). This stock spawned off the west coast of Vancouver Island in 1994, rather than migrating to the traditional spawning grounds off California. The projected long-term increase in temperatures may result in more offshore hake moving into the Canadian zone, and in the spawning and rearing area off California moving north. However, upwelling and nutrient changes may reduce plankton productivity and thus year-class strength. The mechanisms that regulate the abundance of Pacific hake are not known. Therefore, it is difficult to know how abundances will change. If a greater percentage moves north in the summer, the abundance off Vancouver Island may increase over the next 50 years, assuming the stocks are not overfished.

Climate and ocean conditions are associated with year-class strength and migration, but the mechanisms that are linked to climate remain to be determined. There is a joint Canadian and United States process for managing the offshore Pacific hake stock, which could result in overfishing if adjustments are not made quickly during periods of poor recruitment.

In the Strait of Georgia, there has been an increase in Pacific hake abundance in recent years that may be related to an earlier abundance of plankton, resulting in a closer matching of plankton production and spawning activities. Conditions causing the improved survival appear not to be related to reduced Fraser River total flows, but to earlier spring flows and possibly to inflowing bottom water changes. Climate warming will likely result in earlier spring flows, indicating that Strait of Georgia hake will continue to experience high abundance.

Pacific halibut (*Hippoglossus stenolepis*)

Biology

Pacific halibut are a large, fast growing species that can live to a maximum age of 55 years. The maximum size is variable, but lengths to 267 cm and weights to 205 kg have been recorded. They are distributed from southern California to the Bering Sea and across to Japan. At present, the species is fished throughout its range in what may be considered a mature fishery. As a result, few halibut live longer than 30 years, with most being removed before they are 15 years old. The hook and line fishery is managed through the International Pacific Halibut Commission (IPHC) which has operated since 1923. The exploitable biomass is determined annually and quotas are set using a 20% exploitation rate.

Large females can produce up to 3 million eggs annually. Most spawning occurs in winter between December and February, off of the continental shelf at depths of 200–300 fathoms (about 365–550 m). Males mature around 7–8 years, females around 8–

12 years. Fertilized eggs hatch after 15 days. Larvae are free floating in their first few months and have eyes on both sides of their head. During this early stage, one eye migrates to the same (right) side as the other eye. Larval halibut are carried into shallower waters by currents, where they become bottom dwelling. Adults are found from near surface to 600 fathoms (1100 m). Preferred habitat is in sandy and rocky substrates, along reefs and in areas where fish and marine invertebrates are abundant.

Fishery

The Pacific halibut fishery is one of the oldest and perhaps the most successful fishery off Canada's Pacific coast. Canadian and U.S. fishermen started fishing the species commercially in 1888. Catches rose quickly to levels exceeding 30,000 t from 1914 to 1916. An international commission began to oversee the fishery in 1923 because the halibut that were fished in the Canadian and U.S. fisheries were recognized as one population and catches were declining. However, it was not until 1930 that catch was regulated by the commission. Today, the abundance is considered to be at the highest levels in history (Fig. 14A; Clark and Hare, 2002). A historic high abundance of a large, top predator is apparently inconsistent with world trends (Pauly *et al.*, 1998; Myers and Worm, 2003). The Canadian catch is a function of the available quota and effort up to 1977, as fishing was possible off the Pacific coast of the United States. After 1977 Canadian fishermen were restricted to fishing only in waters off Canada (Fig. 14C). The IPHC has reconstructed the exploitable biomass for the total population and for the exploitable biomass of halibut resident off the west coast of Canada, which is at historic high levels (Fig. 14B).

Climate and ocean effects

McCaughran (1997) reported that the productivity of the population declined from 1959 to 1972, consistent with a change in the marine survival after the 1947 regime shift. At this time very high catch rates were set at approximately 38,000 t. At the same time, foreign and domestic trawl fisheries caught and discarded large numbers of juvenile halibut that were incidental to their directed fisheries on other species. The combined effects resulted in historic low levels in 1973. McCaughran (1997) reported that the population would have declined naturally, and that the high fishing rate and large bycatch of juvenile halibut in the trawl fishery simply increased the rate of decline.

Pacific halibut are now known to exhibit a non-random response to environmental conditions in the ocean (McCaughran, 1997; Clark and Hare, 2002). The population will increase when the environment is favourable and the spawning biomass is adequate under the current approach to management. Clark and Hare (2002) showed that inter-annual and decadal-scale environmental variability is the major source of recruitment variability under the current management strategy. Recruitment beginning about age 8 years is related to the particular climate and ocean regime during the spawning year. According to their analysis, the period from about 1947 to 1976 was associated with reduced marine survival, while the period after 1977 was a period of above average marine survival. Another way of wording their conclusion would be to say that fishing does not affect recruitment under the current approach to management, which has a conservative exploitation rate and maintains an adequate spawning biomass. The evidence is convincing that climate changes at the regime scale have been a major influence on the dynamics of the Pacific halibut fishery. There also is evidence that halibut production is related to the lunar nodal cycle (Parker *et al.*, 1995).

Pacific ocean perch (*Sebastes alutus*)

Biology

Pacific ocean perch is the dominant rockfish in the groundfish fishery. However, the rockfish fishery has expanded to include up to 30 species (Table 6), and Pacific ocean perch is now about 30% of the total rockfish catch. Pacific ocean perch is a deep-water bottom species that lives up to 100 years. The age at 50% maturity is about 8 years and fish are thought to be fully recruited to the fishery at age 11 (Leaman, 1988). They are a schooling species that can readily be overfished.

Pacific ocean perch occur in the North Pacific from California to Russia. They are found at a range of depths down to 800 m, but are common between 200 to 400 m. Abundance appears to be associated with preferred temperatures at about 5.5° to 6.0°C. Juveniles may be distributed over a broader temperature range. Pacific ocean perch reproduce through internal fertilization. About September, females retain sperm that is obtained from males, for about 2 months prior to fertilization. After eggs are fertilized, the females move into deeper water (500 to 700 m) until larvae are released, in the late winter or early spring, apparently near the bottom. Young Pacific ocean perch rear in the pelagic areas for several years before moving to deeper water. There is a distinct relationship between size and depth, indicating that older and larger fish continue to move into deeper water. Age at 50% maturity may be between 7 and 9 years and about 25 to 35 cm in length, depending on location. Fish are recruited to the fishery between ages 10 to 15 years. There is clear evidence of strong variation in year classes, which is an indication that the ocean environment strongly affects recruitment.

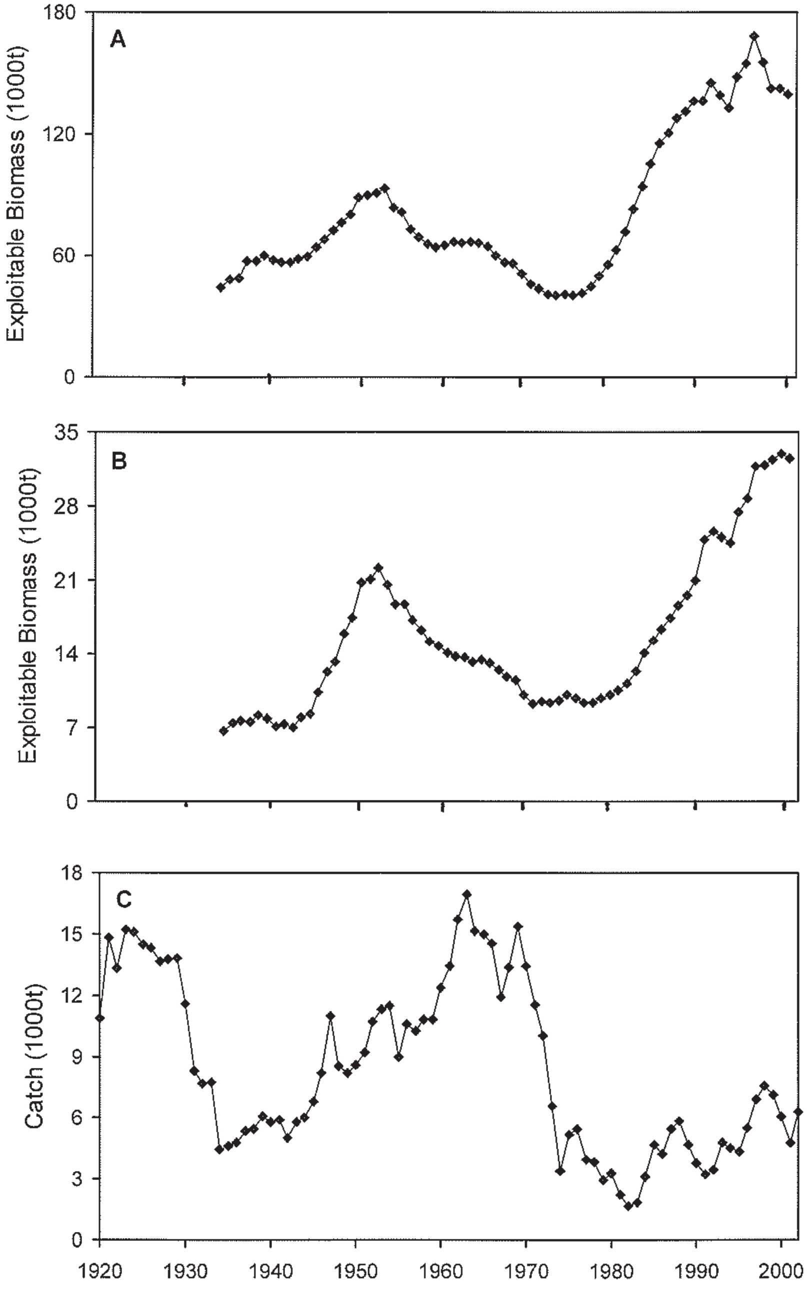

Fig. 14 (A) Exploitable biomass of the total west coast Pacific halibut population from 1935 to 2001; (B) exploitable biomass of Pacific halibut in Canadian waters from 1935 to 2001; (C) Canadian landings of Pacific halibut from 1920 to 2002.

Table 6 Average catch of rockfish by species in the Canadian west coast fishery from 1996 to 2000.

Species	Species name	Average catch (t)
Shortbelly rockfish	*Sebastes jordani*	0.02
Tiger rockfish	*S. nigrocinctus*	0.06
China rockfish	*S. nebulosus*	0.07
Aurora rockfish	*S. aurora*	0.57
Chilipepper rockfish	*S. goodei*	0.22
Dusky rockfish	*S. ciliatus*	0.23
Vermilion rockfish	*S. miniatus*	0.27
Copper rockfish	*S. caurinus*	3.47
Quillback rockfish	*S. maliger*	4.09
Harlequin rockfish	*S. variegatus*	4.25
Black rockfish	*S. melanops*	6.06
Yelloweye rockfish	*S. ruberrimus*	9.00
Rosethorn rockfish	*S. helvomaculatus*	12.16
Greenstriped rockfish	*S. elongatus*	25.16
Darkblotched rockfish	*S. crameri*	51.50
Splitnose rockfish	*S. diploproa*	63.16
Shortraker rockfish	*S. borealis*	65.41
Bocaccio rockfish	*S. paucispinis*	219.43
Redbanded rockfish	*S. babcocki*	247.13
Sharpchin rockfish	*S. zacentrus*	266.27
Rougheye rockfish	*S. aleutianus*	405.35
Shortspine thornyhead	*Sebastolobus alascanus*	579.78
Longspine thornyhead	*Sebastolobus altivelis*	604.61
Canary rockfish	*S. pinniger*	652.90
Redstripe rockfish	*S. proriger*	908.83
Silvergray rockfish	*S. brevispinis*	1173.99
Yellowmouth rockfish	*S. reedi*	1640.40
Widow rockfish	*S. entomelas*	1758.78
Yellowtail rockfish	*S. flavidus*	3988.31
Pacific ocean perch	*S. alutus*	5280.69

Fishery

The history of the Pacific ocean perch fishery prior to 1956 is difficult to document due to poor catch records, and because early rockfish catches were not commonly reported by species (Westrheim, 1987). Thus, it is probable that the early rockfish catches were dominated by Pacific ocean perch. In the late 1950s, Pacific ocean perch were identified in the catch which began to rise due to a dramatic increase in foreign fishing. Total catches increased rapidly from 3,000 t in 1956 to a maximum of 48,600 t in 1966 (Westrheim, 1987), the majority of which was caught by the Russian fleet. At this time, Pacific ocean perch represented over 50% of the total rockfish catches (Forrester *et al.*, 1978). By the time the 200-mile limit was implemented in 1977, the all-nation catches had declined to approximately 6,000 t annually. With the exception of a decrease in catch between 1991 and 1993 due to a change in fishing regulations (Richards, 1994), the Canadian fishery has maintained the catch close to the 6000 t level since the 1980s (Fig. 10E). Overall, the importance of Pacific ocean perch in rockfish catches decreased, beginning in the 1960s. As the fishery expanded into new areas, catches of other rockfish species increased, and catches of Pacific ocean perch decreased. In particular, yellowtail, yellowmouth, and widow rockfish have become increasingly important in recent years (Table 6). However, the proportion of Pacific ocean perch has been maintained at an average of 30% since 1996.

Climate and ocean effects

The effect of regimes on Pacific ocean perch productivity was considered for the first time in a 2001 stock assessment (Schnute *et al.*, 2001). A key finding in the assessment was that trends in Pacific ocean perch recruitment reflected climate regime shifts. Schnute *et al.* (2001) found that production was low prior to 1976, high during 1976–1988, and low again between 1989 and 1998. Currently, there are no strong incoming year classes and the fishery is supported by fish produced during the 1977–1988 regime. If there is a low level of productivity in the post-1998 regime, it is likely that the stock will not maintain itself at current fishing rates. However, the life history strategy of Pacific ocean perch lends itself to slow population growth and decline. Because of this, Schnute *et al.* (2001) stressed the importance of maintaining sufficient adult biomass so that the population can take advantage of future periods of improved recruitment. It is interesting to note that this is the strategy that McCaughran (1997) proposed as the reason for success of the Pacific halibut fishery, and it is a strategy that recognizes regimes of differing productivity.

Pacific sardine (*Sardinops sagax*)

Biology

Pacific sardines have only recently returned to waters off the west coast of Canada. However, Pacific sardines were the largest fishery in the 1930s and 1940s. Historically, sardines entered British Columbia waters in mid-June and returned to southern spawning grounds (California) in mid-October. Most spawning occurred from April to June in the southern California Bight. It was primarily the older, larger sardines that migrated north to feed off British Columbia waters.

Pacific sardines are distributed from northern Mexico to southeastern Alaska, although the main centres of concentration range from southern California–northern Baja California to the southern regions of British Columbia. There are two main spawning areas off southern California and Baja California.

Evidence of sardine spawning in Canadian waters is recent, based on reports of adults with ripe eggs in 1997, 1998, 1999 and 2004, and eggs and larvae taken off the west coast of Vancouver Island in 1992, 1993, 1997 and 2004. Age 0 juveniles (≈ 10 cm) were subsequently collected in March and April of 1998, 1999 and 2004, suggesting successful spawning and rearing in the area.

Sardines reach a size of 15 cm at age 1, 22 cm at age 2, after which growth slows to about 1 cm per year. Females grow faster and larger than males. The largest specimen was 39.4 cm long and weighed 486 g. The maximum recorded age was 13 years. Currently, in the Canadian fishery, few fish are older than 9 years, and most are 3 to 7 years old. Pacific sardines are batch spawners; large fish (21 cm) release 30,000 to 65,000 eggs per spawning. A single large female can spawn about three batches, releasing almost 200,000 eggs per spawning season. About 50% of females are mature at age 1, and 100% by age 2.

The diet of the sardine varies regionally, but as an omnivorous filter feeder, it includes copepods, diatoms, a variety of other zooplankton, and occasionally fish larvae.

Fishery

The fishery for Pacific sardines started in British Columbia in 1917 and quickly became the largest fishery on Canada's Pacific coast with catches averaging about 40,000 t (Fig. 15A and B). The Pacific sardines fished in Canadian waters were part of a population that was most abundant from southern California to southern British Columbia. The population off Canada's west coast consisted of older and larger fish that migrated north in early summer (Hart, 1943) and returned south in the fall. The sardines fished off Canada were believed by some to be part of a genetically distinct population that spawned at the northern limit of the spawning distribution in the south (Felin, 1954; Radovich, 1982). Others believed that it was one population in which the older fish migrated successively farther north as they aged (Schweigert, 1988).

The Canadian Pacific sardine fishery was concentrated from the late 1920s to the mid-1940s off the west coast of Vancouver Island, and extended

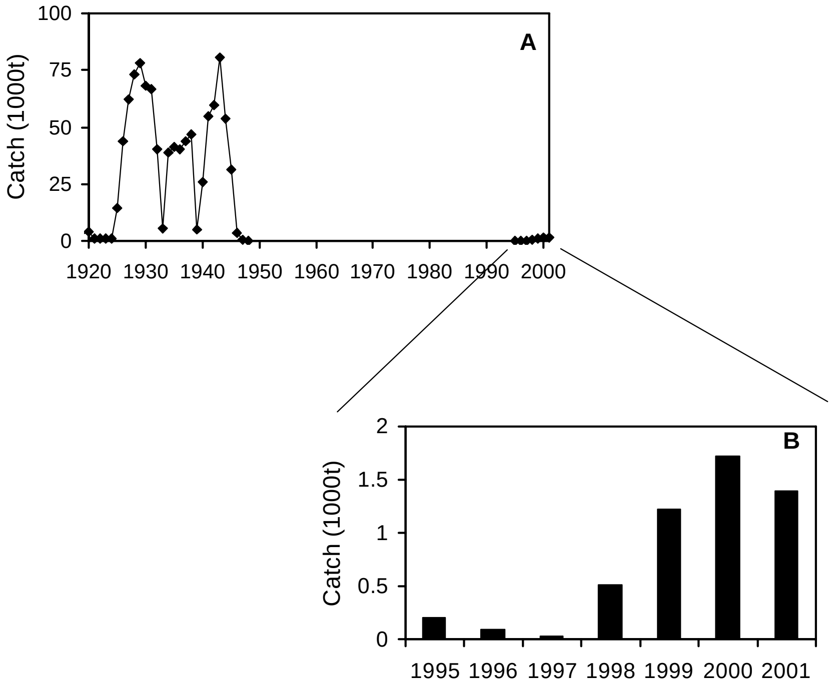

Fig. 15 (A) Catch of Pacific sardine in Canadian waters from 1920 to 2001; (B) combined research and fishery catches of Pacific sardine from 1995 to 2001 (updated from McFarlane and Beamish, 1999).

south to Washington State. Virtually all of the catch was reduced into fish meal and oil. The Canadian and U.S. fisheries in the 1930s and 1940s combined to become the largest fishery in both countries (Wolf, 1992). The Canadian fishery collapsed suddenly in 1947, followed rapidly by the collapse of the U.S. fisheries which collapsed by 1951 (MacCall, 1979). Initially the collapse was blamed on overfishing, but recently the collapse was regarded as another example of overfishing at a time of unfavourable environmental conditions (MacCall, 1979; Ware and Thomson, 1991). The mechanism responsible for the natural decline remains to be discovered, but a clue is the amazing synchrony in the abundance fluctuations among the sardine fisheries in the Pacific Ocean off Japan, Chile, and North America (Kawasaki, 1991). It is important to note that virtually no Pacific sardines were reported from waters off Canada after the collapse through to the early 1990s (Hargreaves *et al.*, 1994). The population of Pacific sardines to the south of Canadian waters started to increase in the late 1970s. Beginning about 1992, Pacific sardines appeared off the west coast of Canada (Hargreaves *et al.*, 1994; McFarlane and Beamish, 1999). The increase in abundance persisted through to the present and reflects a dramatic increase in the general population (McFarlane and Beamish, 1999; McFarlane *et al.*, 2000). In recent years, a small fishery for Pacific sardines occurred off the west coast of Vancouver Island (Fig. 15B). It is now generally accepted that the fluctuations in Pacific sardine abundance off Canada are related to climate and climate changes on a decadal scale. Fishing in Canada and the United States exacerbated the natural decline of this short-lived species (Radovich, 1982) but it was a change in climate that started the decrease in the late 1940s, and the increases in the late 1970s.

Climate and ocean effects

Kawasaki and Omori (1986) recognized synchrony in the trends of abundance of sardine populations off Japan, California and Chile. The collapse of sardine stocks off Canada and the United States in the late 1940s corresponded to the collapse off Japan. Beginning in the late 1970s, the stocks off Japan, California and Chile synchronously increased in abundance. Stocks declined off Chile and Japan in the late 1980s and early 1990s, but those off California have not done so yet. The results of Kawasaki and Omori's study (1986) indicate that large fluctuations in sardine populations are a consequence of large-scale changes in the climate and ocean factors affecting their carrying capacity.

In 1992, sardines reappeared in British Columbia waters and were captured in both commercial and research catches of Pacific hake (McFarlane and Beamish, 1999). Their abundance was determined to be large enough to initiate an experimental commercial fishery in 1995. Movement into the Canadian zone may be continuing because sardines are moving farther north each year. The large abundance of sardines in the Canadian zone was observed prior to the major increase in temperature of the surface waters as a result of the 1997 El Niño (occurring in August and September) and persisted off British Columbia through 1998. At the same time as large numbers of sardines appeared off British Columbia, the total abundance off California remained stable (450,000 t). Catches off California have been maintained although catch decreased in 1998. Sardines remained abundant and spawned off the west coast of Vancouver Island in 1998 even though El Niño conditions did not persist. The El Niño events in the 1950s through to the 1980s were not associated with changes in sardine movement and spawning biology. Thus, while movement of sardines into areas of British Columbia may be associated with recent El Niño events, it is likely related to other changes in the ecosystem. The changes in sardine distribution, abundance and spawning (and the similar changes in mackerel and hake) indicate that a shift in the dynamics of the ecosystem off British Columbia occurred in the early 1990s.

Pacific cod (*Gadus macrocephalus*)

Biology

Pacific cod are widely distributed in the coastal North Pacific from the Bering Sea south to Santa Monica, California, and west to the Japan/East Sea. Pacific cod grow rapidly in the first year, reaching 30 cm by age 1, and are sexually mature by 2 to 3 years old (Westrheim, 1987). Length at first maturity is approximately 40 cm, and length at 50% maturity is 55 cm. Pacific cod tend to disperse into deeper waters to feed, and congregate to spawn in shallower waters from February to March. They undergo a seasonal migration from shallow waters in the spring and summer to deeper waters in the fall and winter. Pacific cod in Canada are at the southern limit of their distribution and are therefore vulnerable to the expected climate and ocean changes. Four stocks of Pacific cod are defined for management in British Columbia: Strait of Georgia, west coast of Vancouver Island, Queen Charlotte Sound and Hecate Strait. In Hecate Strait, stock abundance remains at historic lows, recruitment of the last 9 year classes has been below historic levels, and the 1998 year class was the smallest ever. Abundance off the west coast of Vancouver Island also remains low. Pacific cod were common in the Strait of Georgia in the past. Presently, few fish remain, possibly because of the increase in water temperatures in recent years.

Fishery

Small Pacific cod fisheries take place in Queen Charlotte Sound and off the lower west coast of Vancouver Island. The major fishing occurs in Hecate Strait. Pacific cod spawning stock biomass and recruitment has been estimated for Hecate Strait using stock reconstruction based on ages estimated from lengths (Haist and Fournier, 1998), on which management actions were based. The species is a significant component of the multi-species groundfish fishery in Hecate Strait. Annual yields have varied between a high of 8,870 t in 1987 to a low of approximately 200 t in 2001. Landings since the mid-1990s have been very low (Fig. 10I). The trawl fishery has undergone a number of significant changes in recent years. Prior to 1992, the total catch of Pacific cod was unrestricted and the main management measures were area and season closures. Total allowable catches were introduced in the Hecate Strait area in 1992, in response to declining abundance. Trip limits were also introduced in the same year and these decreased steadily until 1995. For the 1996 season, trawl catches were limited to bycatch only because of stock concerns. Stock declines resulted from a decade of below average recruitment. The pattern of recruitment (age 2+) off the west coast of Vancouver Island from 1960 to 1988 was similar to that of Hecate Strait with the recent regime (1989–1997) characterized by 9 years of very poor recruitment.

Climate and ocean effects

High sea levels in Prince Rupert area are associated with high transport through Hecate Strait, resulting in poor recruitment for Pacific cod. Sea levels were high in the Prince Rupert area up until 2003, when they began to decline. The relationship between sea level and recruitment can be interpreted as an indication of the sensitivity of Pacific cod recruitment to ocean conditions. Bottom temperatures in the range of 6° to

7°C appear to be optimal for Pacific cod recruitment. Temperatures higher than 7°C will likely decrease recruitment. Laboratory studies on the effect of temperature on Pacific cod egg survival indicate that the optimal temperature is between 3.5° and 4°C with an acceptable range of 2.5° to 8.5°C (Alderdice and Forrester, 1971). Bottom temperatures in February that exceed 8.5°C would most probably reduce or eliminate recruitment. The southern limit of the commercial abundance of Pacific cod is northern Oregon and the southern limit of landings has been southern Oregon. Thus, there is little doubt that Pacific cod in British Columbia are at the southern limit of their distribution and are a sensitive indicator of temperature increases.

One method of monitoring the impacts of a changing climate is to identify a few species that are common to a large number of areas, and that respond quickly to a changing climate. Species should be commercially important so that continuous sampling is not a problem. There also should be a sound understanding of biology and some insights into the mechanisms that naturally regulate abundance. Pacific cod are a good indicator species in the Canadian zone.

Pacific salmon

We highlight the biology and fishery of pink, sockeye, and chum salmon. We assess the impact climate and ocean effects, along with global warming effects, in a combined discussion for all species, including coho and chinook in a section following the species summaries.

Pink salmon (*Oncorhynchus gorbuscha*)

Biology

Pink salmon are the most abundant of the Pacific salmon in British Columbia waters and in the all-nation catches of Pacific salmon. They have the shortest life span, approximately 2 years from hatching, and are the smallest salmon species. Pink salmon form distinct spawning brood-lines with some stocks spawning in years with even numbers (*i.e.*, 1996) and some with odd numbers (*i.e.*, 1997). The largest stocks of pink salmon occur in the Fraser River, where spawning occurs only in odd-numbered years. Farther north, spawning occurs in all years with a tendency for the even-year spawning stocks to predominate. Although pink salmon occur farther south than British Columbia, the centre of distribution is north of British Columbia. Fraser River stocks, therefore, are close to the southern limit of the range.

Females may produce 1,200 to 1,900 eggs depending on the stock and female body length. Spawning occurs from July through to early fall in riverbeds with coarse gravel. Pink salmon prefer to spawn in swift currents along the borders of streams or in riffle areas.

Fishery

Pink salmon are not highly esteemed in British Columbia, thus catches probably are not a good indicator of abundance. This is particularly true in recent years when there has been exceptional production in some stocks with virtually no commercial fishery. In Canada, total annual catches of pink salmon averaged 19,700 t, or approximately 14.7 million fish, from 1959 to 2000. Total catches of pink salmon increased after the 1977 regime shift, reaching a maximum in the early 1990s (Fig. 16). Since the early 1990s, there has been a dramatic reduction in catch.

A recent analysis of the coast-wide production of pink salmon indicated that over the past decade, the spawning abundances may have doubled or tripled compared to numbers in the 1960s and 1970s (B. Riddell, personal communication). Pink salmon produced in the Fraser River historically accounted for about 60% of the total British Columbia catch, although some of this 60% is caught by the United States. Their population dynamics and the response of the fishery is probably a good indicator of the dynamics of most pink salmon stocks. Virtually all stocks of pink salmon in the Fraser River spawn in odd-numbered years. The reason for the persistent dominance of these “odd-year stocks” and the general phenomenon of dominance among pink salmon stocks is unknown. In 2001 and 2003, there was a large return of pink salmon to the Fraser River. Management policy resulted in an exploitation rate on this return that was very low, resulting in a spawning escapement that was approximately two times the highest estimated escapement on record. These exceptional returns were produced from one of the lowest escapements on record in 1999. Clearly, there was a dramatic increase in the marine survival of pink salmon fry entering the Strait of Georgia in 2000.

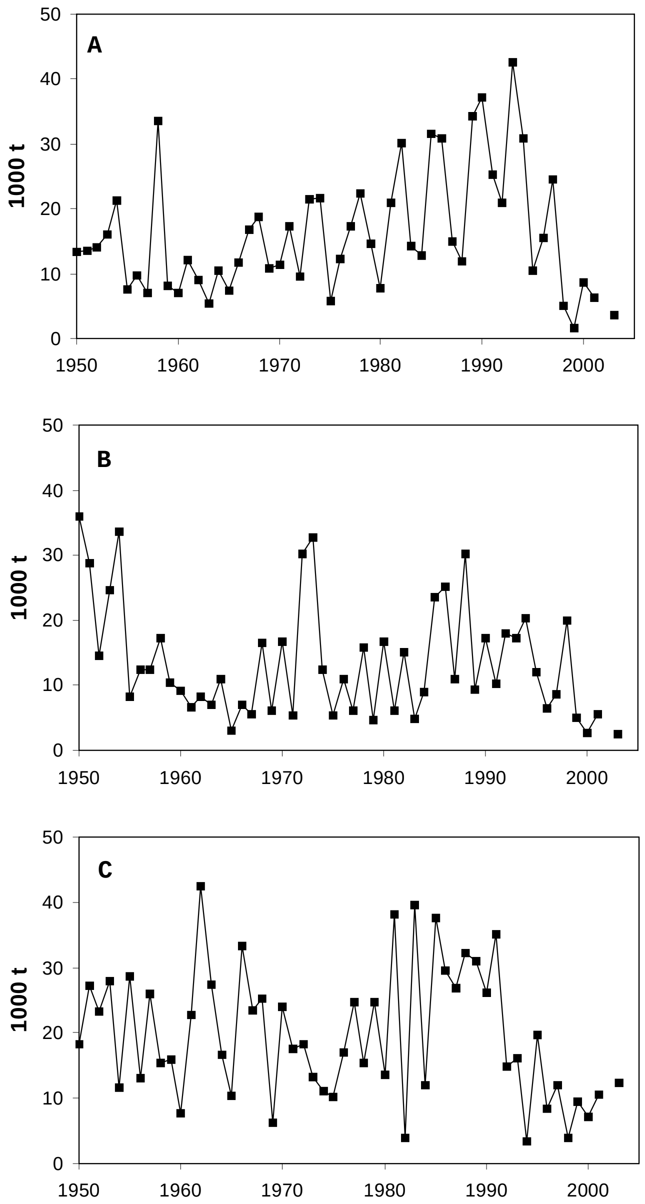

Fig. 16 Canadian catches of (A) sockeye salmon, (B) chum salmon, and (C) pink salmon.

Sockeye salmon (*Oncorhynchus nerka*)

Biology

Sockeye salmon are probably the fish that is of most interest to British Columbians. The Fraser River stocks have averaged about 80% of the British Columbia sockeye production and 25% of the catch of all salmon in British Columbia. These sockeye stocks can be considered to be at the southern edge of this species' range and are susceptible to changes in both the freshwater and marine environments.

Most sockeye salmon return to the Fraser River in July and August and spawn in the fall. After hatching, alevins emerge in the spring and migrate into nearby lakes. After a year in the lake, most sockeye migrate in the spring to the ocean, where they grow and undertake extensive migrations before returning to spawn 2 years later. There are variations to this generalized life history (Foerster, 1968), but it is always a combination of a prolonged dependence on fresh water followed by a period of ocean residence of 2 to 3 years.

Fishery

Catches of sockeye follow a cyclic pattern. Sockeye production in the Fraser River follows a 4-year cycle (Foerster, 1968). For example, in 1997 there was the largest return of sockeye salmon in the 4-year cycle from 1994 to 1997, with fewer returns in 1998. For the first half of the 20th century catches were variable, but relatively stable. The total catch of sockeye salmon was low from about 1950 to 1975. The lowest catches occurred in 1965 and 1975. Catches increased dramatically, beginning in the late 1970s, with the record catch of 42,500 t in 1993 (Fig. 16), but declined quickly in the 1990s. The lowest catches on record of 1,710 t occurred in 1999. The declining trend in recent years is largely a result of reduced Fraser River sockeye production, since total production estimates for sockeye salmon from the Skeena and Nass Rivers from 1970 to 1996 (Wood *et al.*, 1997) illustrate that production increased in these northern rivers in the 1990s. The 1989 regime shift has been associated with some of the lowest catches in the history of the fishery and the change is seen primarily in the southern stocks. A study by Beamish *et al.* (2004b) showed that the stock and recruitment relationships for Fraser River stocks are closely related to climate regimes. The mechanism linking climate to marine survival may be growth in the first marine year (Beamish *et al.*, 2004b).

Chum salmon (*Oncorhynchus keta*)

Biology

Chum salmon may exist in about 800 rivers in British Columbia (Salo, 1991). There are distinct summer and fall spawning stocks, with runs in the north being earlier than in the south. In the south, spawning can occur from October to January. The general biology of chum salmon in British Columbia is similar to chum in other areas. In the spring, chums are some of the first salmon to enter the ocean, remaining in the nearshore areas until the end of May (Healey, 1980). They then move into more coastal waters and by mid-summer they leave the inshore areas and migrate offshore and into the Gulf of Alaska (Hartt and Dell, 1986). In recent years they have remained inshore in large numbers through to mid-September (Beamish and Folkes, 1998). Most chum salmon (about 60%) spend three winters in the ocean. The remaining fish spend 2 or 4 years at sea, with very few spending 5 years at sea. The average size at return is about 70 to 75 cm. Since the late 1970s, chum salmon have been produced in hatcheries. The total production reached a maximum in the early 1990s, and in recent years has declined. Chum eggs are hatched in hatcheries and the fry are fed in channels prior to release. In some cases the fed fry are placed in sea pens and reared in salt water prior to release.

Fishery

Chum salmon are generally the last species caught in the commercial fisheries. Most fisheries occur near river mouths, or what are called “terminal areas.” Fishing is with purse seines or gillnets. Smaller fisheries occur using troll gear. Chum salmon that retain their “silver colour” are frequently marketed for smoking. Those that are coloured externally are valued only for their roe. In recent years, catches increased in the late 1980s through to the early 1990s (Fig. 16). Catches were low in the mid- to late 1990s through to the present. Assessments of total production generally show that it has been stable for the past 30 years (Godbout *et al.*, 2004; Spilsted, 2004).

Impacts of Global Warming on all Pacific Salmon in the Fishery

Pacific salmon remain as the group of species that are of principal interest to British Columbians even though their commercial value has declined substantially. It is useful to assess the impact of climate changes on all species of Pacific salmon, rather than assessing the impact only on sockeye salmon, which remains one of the most important species in the commercial salmon fishery. The specific factors that regulate salmon abundance are not clearly identified, making it difficult to predict the impacts of altered ecosystems. Changes that could occur in fresh water as a consequence of climate change would have a major impact on Pacific salmon. These would impact on the migrations, spawning, hatching, and early rearing phases. Physical changes in temperature, precipitation, groundwater discharge, and increased ice-free periods for lakes could affect community structure and the survival, growth, and distribution of salmon species (Meisner *et al.*, 1987; Glantz, 1990; Magnuson *et al.*, 1990; Chatters *et al.*, 1991; Neitzel *et al.*, 1991; Northcote, 1992).

The Fraser River drainage in British Columbia is a major producer of Pacific salmon, accounting for 30 to 40% of all Pacific salmon produced in Canada. Because numerous stocks of the five species of salmon are at or near the southern limit of their range, the early impacts of climate change should be detectable in these stocks. Levy (1992) investigated these potential impacts by formulating eight hypotheses and considering the possible responses of salmon to climate change. His hypotheses can be summarized as follows: a warmer climate will increase water temperatures and decrease flows during spawning migrations, increasing pre-spawning mortality and reducing egg deposition. A warmer climate will increase water temperatures during egg incubation stages, causing premature fry emergence and increased fry-to-smolt mortality. At the same time, a warmer climate will increase the severity and frequency of winter floods, thereby reducing egg-to-fry survival rates. The productivity of lakes will be altered, but impacts on their suitability as nursery habitats for juvenile sockeye salmon is not known.

It is highly probable that there will be a direct relationship between increased river temperatures and pre-spawning mortalities for all salmon. In fact, in the late 1990s, abnormally high pre-spawning mortality occurred, and one of the explanations related the mortality to changes in climate. The impact of climatic warming on winter water temperatures is uncertain. Winter water temperatures are related to groundwater base flows, lake water runoff, precipitation levels, and perhaps changes in snowmelt patterns. It is probable, however, that both summer and winter temperatures will be higher. These changes are particularly relevant for coho and chinook salmon, which remain in fresh water during their first year after hatching. Warm summer water temperatures may be too high for optimal growth and may force the young salmon into suboptimal habitats. Poor growth in fresh water may contribute to increased mortality in the ocean. Coho salmon are vulnerable to warming because their embryonic development is sensitive to warm winter temperatures (Murray *et al.*, 1990).

Pacific salmon are particularly susceptible to temperature fluctuations because they have adapted to thermal regimes in both fresh and salt water. At the southern limits of salmon distribution, projected climatic changes would warm both marine and freshwater habitats, especially in the winter. High temperature has a profound effect on fishes because they cannot regulate their body temperature. Extreme temperatures may kill eggs, juveniles, or adult salmon; less extreme temperatures can affect growth, reproduction, and movement. Recommended temperatures for most Pacific salmon in fresh water range from about 7° to 16°C (Reiser and Bjornn, 1979), with extremes from 3° to 20°C. Upper lethal temperatures are 25° to 26°C. Southern rivers could approach these higher limits under projected climatic scenarios. In the marine phase of the life history of salmon, there are critical temperatures of 9° to 10°C that restrict feeding areas for salmon to areas cooler than these temperatures (Welch *et al.*, 1995). Ocean warming, particularly in the winter, could favour northern areas for the rearing of salmon.

Stream discharge patterns have a high degree of variation, and changes in the variability of timing and the expected increase in variation could reduce the accuracy of management and result in the need for reduced exploitation rates. Virtually all sockeye salmon spawn in rivers that flow into or out of lakes. After hatching, fry move into the lake where they must remain for a minimum of one year. Although there is uncertainty about how lakes will respond to a warmer climate, sockeye salmon in the Fraser River are at the extreme southern limit of their distributions and will be sensitive to changes in limnological conditions. Excessive warming may affect the ability of young sockeye to grow to the sizes necessary for survival in the ocean.

Warming of fresh water in the north may improve production. Much of the increases in total Pacific salmon abundance in the 1980s occurred in Alaska stocks, possibly indicating that warming in fresh water and coastal areas at this time was beneficial for salmon production. However, the function of northern aquatic systems has not been well documented, and large temperature increases could have unforeseen effects on Pacific salmon survival.

Beamish and Noakes (2004) examined the role of climate change on the past, present and future of Pacific salmon species off the west coast of Canada. They suggested that existing stock assessment models might be inadequate to predict the dynamics of a stock in a future of climate change. They provided one scenario that predicts an increase in the total production of Pacific salmon as climate changes. This contrasts with other interpretations, such as that of Welch *et al.* (1998), who used estimates of sea surface temperature increases to propose that the ocean habitat available to sockeye salmon would diminish and would move farther north. Both scenarios are possible and need to be evaluated as climate changes become more extreme. Beamish and Noakes (2004) also noted that Pacific salmon may move into the Canadian Arctic in increasing numbers.

Pacific salmon are well known for their homing ability from feeding areas in the open ocean to the exact areas of their birth in coastal freshwater rivers (Groot and Margolis, 1991). Less well known is their ability to stray. This straying rate can range up to 10% (Groot and Margolis, 1991), and it provides Pacific salmon with an ability to adapt to large-scale climate change such as past periods of glaciation. All five species of Pacific salmon have been reported in Canadian Arctic waters (Hunter, 1974; Craig and Haldorson, 1985; Babaluk *et al.*, 2000), with pink salmon being the most frequently observed and chinook salmon the least frequently seen. Babaluk *et al.* (2000) reported the first records of sockeye and pink salmon from Sachs Harbor on Banks Island in the Beaufort Sea. Although Pacific salmon had been observed in this area previously, the report of Babaluk *et al.* (2000) represented extensions of these earlier records. One report of a coho salmon caught on Great Bear Lake on 25 September, 1987 represented an extension of 1500 km east of an earlier report at Prudhoe Bay, Alaska (Craig and Haldorson, 1985). These reports are noteworthy because they highlight the rare occurrence of Pacific salmon in the Arctic; however, they also indicate that straying is occurring.

The Arctic is one area that may be exhibiting early impacts of global warming. Model predictions are that a doubling of CO_2 would reduce the extent of sea ice by 60% and the volume by 25 to 45% (Gordon and O'Farrell, 1997; IPCC 2007). There would also be greater freshwater runoff. During the period 1978–1996, there was a 2.9 to 3.5% per decade decrease in the extent of Arctic Sea ice (Cavalieri *et al.*, 1997; Serreze *et al.*, 2000; IPCC 2007). If such dramatic changes continue, conditions favorable to straying and perhaps feeding for Pacific salmon may improve.

In general, it is probable that the response of stocks north of 50° to 55°N will be different than stocks south of this area, based on a historical oscillation in productivity between northern and southern stocks (Hare *et al.*, 1999). We speculate that in the future the importance of this oscillation will diminish as the southern stocks struggle to adapt to a climate-related variability that currently exists south of the existing limits of Fraser River stocks. We expect that sockeye salmon and other Pacific salmon stocks in the Fraser River will be severely impacted, as they are virtually at their southern limits. It is important to remember that Pacific salmon are anadromous. The impacts will be in both fresh water and the ocean. In the ocean, we expect that the major sources of early marine mortality will become more variable and more extreme. Predation may increase as more pelagic predators, such as Pacific hake and mackerel, move north. Growth-based mortality (Beamish and Mahnken, 2001) may become more important and more variable. It may be possible to mitigate climate-related changes in fresh water; however, adjusting management to adapt to climate-related changes in the ocean would range between challenging and impossible. Nonetheless, if climate-related impacts could be identified quickly, it may be possible to use this information to convince Canadians and other countries that reductions in greenhouse gases are essential for the protection of Pacific salmon at their southern range.

Species, such as coho and chinook salmon, should be less impacted because these two species are not at their southern limits in British Columbia. However, these are the two species that are most affected by hatchery production (Sweeting *et al.*, 2003). It should be apparent that the fundamental scientific assumptions used in the management of Canada's Pacific salmon stocks must change. The ocean's capacity to produce salmon is now known to be an important consideration. This means that management must now consider the impacts of both fishing and climate–ocean changes on an aggregate of stocks of species in marine ecosystems. In hindsight, our expectations for the Pacific salmon resource on Canada's west coast in the 1990s were not even close to what occurred. Similarly, we know of no one who predicted that in 2001, the salmon returns to the Columbia River would be the largest on record and chinook salmon returns the largest since 1973 (Wakefield, 2001). Thus, we need to accept that our fisheries management science is not adequate to describe the factors that regulate Pacific salmon populations. The certainty of the future is that there will be continued change and that robust strategies need to be developed if we are to adapt successfully to both natural climate change and the modifications caused by human-produced greenhouse gases.

The short life span of pink salmon of 2 years between spawning, as well as their abundance and extensive distribution, makes pink salmon a desirable species for studies of environmental impacts such as greenhouse gas-induced climate change on the long-term population dynamics of all Pacific salmon. This increase in marine survival in 2000 coincided with a major shift in the trend of climate indicators. Thus, there is solid evidence that pink salmon respond to climate changes in a time frame that could be used to detect the impacts of greenhouse gas-induced climate change. Pink salmon are an excellent indicator species because they are distributed throughout the subarctic Pacific and there is a long history of careful management. The single year class and the short life span facilitate associations between climate change and estimates production. Additionally, the tendency for pink salmon to stray may also become an important indicator of factors affecting distributions.

We modified Levy's (1992) hypotheses that evaluated the linkages between climate and biological systems that could be used to plan for managing fragile northern freshwater and marine ecosystems in a warmer climate (Table 7). This table of possible impacts could be used to develop plans for the impacts of climate change on salmon fisheries throughout the range of Pacific salmon.

Impacts of Global Warming on the Key Non-salmon Species in the Fishery

A difficulty in forecasting climate change impacts on fisheries in British Columbia is the inability to obtain model outputs at a regional scale. It is also necessary to integrate modes of natural climate variability in the model scenarios for greenhouse gas-induced change. There is ample evidence that the recruitment of many species of west coast fishes is affected by these modes of natural variability. Therefore, it makes sense that they must be included in model formulation.

One way of assessing the impact of future climate change is to try to use past changes in the population dynamics of a species to identify future climate-related impacts. There are two major difficulties with this approach. One is that it is necessary to identify the impacts of fishing. To do this, assumptions are made about stock and recruitment relationships which assume that climate and ocean

Table 7 Potential impacts of global warming on Pacific salmon biology, life history and population dynamics in British Columbia.

Fresh water	Salt water
- Earlier timing of returning adults	- Earlier time and size of ocean entry
- Earlier time of entry into rivers	- Changes in predator composition
- Higher river temperatures	- Changes in ocean productivity will affect species differently
- River flow rates	- Changes in growth in the first marine year
- Reduced access to spawning areas	- Changes in juvenile migratory routes in response to temperature
- Earlier changes in the hatching times	- Increase in temperature
- Changes in the productivity of freshwater ecosystems, - Impact of species new to the ecosystem	- Decrease in salinity, - Changes in the Aleutian Low and Pacific Decadal Oscillation that are currently unknown
- More variability in growth	- Earlier timing of spring transition
- Increased percentage of hatchery salmon	- Changes in competitors for food, - Reduced marine growth
- Reduced ability to adapt to changes in habitat	- More variability in straying rates, - Loss of ability to adapt because of the loss of wild fish

effects are random. For example, the assumptions for the standard Ricker curve are that density-dependent effects occur in fresh water (Ricker, 1954) and that there is no trend in the climate-related impacts (Ricker, 1958). It is also virtually impossible to determine the objectives of fisheries management for the future.

A second difficulty is that past climate trends are probably not a guide to the trends expected in the future. Thus, if new climate states are to be expected, particularly more frequent extreme events, we should also expect new impacts. Nevertheless, it is useful to consider how past changes in population dynamics might have been affected by climate, not necessarily as a guide for future interpretations, but as evidence that we can no longer view fishing impacts as the only factor affecting abundance, and that we will need to be vigilant in our monitoring and evaluation of future changes in fish stocks. We estimate the impacts of climate change using our understanding of the biology of a species, our interpretation of the past impacts of fishing relative to the impacts of the ocean environment, and our belief that regimes and regime shifts are important and will become even more influential. We used average values of climate change taken from the Third Assessment Report of the IPCC and consider how these changes could influence the environment of the major species in the fishery (Table 5). A summary of the following impacts is included in Table 8.

Sablefish

Because adult sablefish appear to be able to adapt to natural short- and long-term shifts in ocean conditions, it is probable that global warming will not have impacts on adult sablefish in a time frame of 50 years that will threaten the long-term dynamics of the population. This does not mean that specific global warming impacts on the survival of eggs, larvae and juveniles will not occur; rather, that the adult fish may be able to survive such adverse conditions. Also, there will be time to detect changes in the population dynamics and to consider management options, but this does not mean that the population will be able to support current levels of exploitation, particularly at rates of around 15%.

An immediate concern is the impact of fishing on the population structure and the natural ability of sablefish to survive in unfavourable conditions. Fishing impacts over the past 30 years have reduced the percentage of older fish in the population. Presumably, the remaining fish still have the ability to live for extended periods; however, there may be some changes in their biology if the fishery is in some way exerting a selective force on the genetic composition of the population. If the impacts of global warming are negative and reproduction is less successful or fails, it may be important to ensure that a percentage of the existing population is allowed to live to the older ages that existed prior to commercial fishing. This may be best accomplished by establishing no fishing zones that are in the most favourable spawning areas. If periods of intense Aleutian Lows increase as a consequence of global warming, there is a possibility that recruitment periods may increase relative to the past 50 years.

Pacific herring

A key factor regulating abundance of Pacific herring appears to be predation (Ware and McFarlane, 1995; McFarlane *et al.*, 2001). A major predator is Pacific hake, which are at the northern limit of their distribution in British Columbia. It is possible that more hake will migrate farther north as the coastal areas warm. This will result in more predation on herring, providing offshore hake stocks are not overfished and reproduction off California and Oregon is not severely impacted by changes in ocean productivity.

The present management strategy for herring allows fishing only when abundances are above a minimum spawning biomass. This strategy should be adequate to adapt to the uncertainty of the impacts of greenhouse gas-induced changes. Recruitment levels have been estimated as part of annual stock assessments (Schweigert, 2001), and those estimates can be used to identify relative year-class strength. Since 1972, there are some consistent patterns in herring productivity, but the patterns are less clear than for other species. For herring in all five management areas, the regime shift years 1977 and 1989 were years of good recruitment, as was 1985, a year of very intense Aleutian Low pressures. Generally, the regime prior to 1977 had better recruitment than from 1977 to 1989. After 1989, recruitment in the Strait of Georgia has generally been above average, but recruitment continued to be poor in the other four areas until 1994. The poor recruitment during the 1977–1988 regime could be associated with the observed shifts to warmer SSTs; however, it can only be one indicator of the mechanism since Strait of Georgia stocks increased in the 1990s despite continued warming.

It is tempting to conclude that herring are quite adaptable and may increase in abundance in some areas and decrease in others, possibly maintaining the current catch levels. An important consideration is the commercial fishery removals. The current fishery appears to be conservative and well managed with specific “cut-off” levels below which no fishing is allowed. In addition, the demand for product is much less than in the 1950s and 1960s. Thus, it is likely that the pressure to overfish that occurred in the

Table 8 Summary of potential impacts of greenhouse gas-induced climate change on key species in the British Columbia fishery in the next 50 years.

Species	Potential impact
Sablefish	Stocks in the south may be reduced, but the northern stock may benefit from more strong year classes. A key factor will be the protection of the spawning stock from overfishing. If overfishing does not occur, the adult population should be able to survive prolonged periods of poor recruitment over the next 50 years.
Pacific herring	Stocks in the Strait of Georgia should remain at high levels, but offshore stocks would be reduced by increased predation.
Pacific hake	The Strait of Georgia stock should continue at high abundance. The offshore stock should also remain at higher abundance levels provided it is not overfished. If abundance increases, more fish will move farther north, perhaps off the Queen Charlotte Islands and into Queen Charlotte Sound.
Pacific halibut	The abundance within the population should remain at high levels as a consequence of a stormier North Pacific in the winter. The abundance off Canada may be reduced slightly as fewer juveniles migrate farther south.
Pacific ocean perch	The major impact will be increases in the frequency of strong year classes which will improve abundance.
Pacific sardine	In the Northeast Pacific, Pacific sardine abundances follow trends that are associated with the spawning and rearing environment off California and Mexico. The mechanisms remain unknown. If the Aleutian Low intensifies, it is possible that the trends in sardine production may continue, perhaps with increased production during favourable periods. Off British Columbia, Pacific sardine will increase in abundance and may establish resident populations in increasing productivity regimes, but the natural fluctuations will still occur. This means that one of the future regime shifts will result in conditions unfavourable for sardine reproduction and a natural collapse will occur. However, there may be residual stocks of sardine that reside longer, or all year, in the Canadian zone as more sardines move north into it in the summer.
Pacific cod	Pacific cod will gradually disappear from the Strait of Georgia and off the west coast of Vancouver Island as bottom temperatures warm.
Pacific salmon	Pacific salmon from the Fraser River stocks will suffer major impacts in fresh water and in the ocean. Sockeye, pink and chum from the Fraser River will be reduced in abundance as a consequence of reduced freshwater survival as juveniles and spawning adults. The production of wild coho and chinook will also be reduced, but the reduction will be less than for the other species. Pacific salmon stocks from the Skeena and Nass rivers and to the north will increase in abundance as a result of improved ocean productivity. Pacific salmon will begin to reproduce in Arctic rivers. Pink salmon will be excellent indicators of climate-related change. Basin-scale changes in growth, survival, and straying rates will all indicate when large-scale changes occur.

1960s will not be a factor. We propose that the herring population in the Strait of Georgia will continue to be high as long as Pacific hake remain abundant and have a small size at age (*i.e.*, no predation on herring). On the west coast of Vancouver Island, the abundance of herring will fluctuate, but will generally remain low as a consequence of Pacific hake predation that could extend much farther north and reduce abundances off the Queen Charlotte Islands. However, we emphasize that fluctuations will be common, as Pacific hake appear to be one of the key regulators of abundance. In the next 50 years, Pacific herring stocks will likely continue to fluctuate in abundance more or less in a manner similar to the dynamics observed during the past 25 years.

Pacific hake

There are two distinct and major populations of Pacific hake, one in the Strait of Georgia, and another off the west coast of Vancouver Island. There are also numerous small abundances of Pacific hake in the inlets along the British Columbia coast. The Strait of Georgia has been warming since the 1960s but the reasons for the warming have not been determined. Pacific hake in the Strait of Georgia have increased in abundance during this warming period and, at the same time, decreased their individual size. We expect that the Strait of Georgia will continue to warm. We also expect that the synchrony of improved primary production and intense Aleutian Lows or PDOs will continue, and even become more favourable for Pacific hake production. Thus, Pacific hake will continue to be the dominant species in the Strait of Georgia and their individual size will remain smaller.

Pacific hake off the west coast of Vancouver Island migrate into the Canadian zone from areas off California and Oregon. Impacts of global warming will affect the amount of production, the numbers that migrate into the Canadian zone, and the northern extent of their migration. As with Pacific sardine populations, an increase in the intensity of the Aleutian Lows and mid-ocean upwelling (as occurred in the 1980s) would result in an increase in the number and strength of above-average year classes, and subsequently mature biomass. Increased warming in coastal waters will result in a greater proportion of mature fish migrating north into Canadian zone. In addition, the extent of this migration will move farther north. For example, the increase in temperature during the 1990s resulted in approximately 40% of the mature stock entering the Canadian zone, compared to 25% during the 1980s. In some of the years (1992, 1993, 1997, 1998) commercial quantities of Pacific hake were common in northern British Columbia waters, and in at least two of the years (1997, 1998), were captured in the Gulf of Alaska.

Pacific halibut

Pacific halibut are currently distributed from California to the Bering Sea, thus they are able to tolerate a wide range of temperature as adults. The expected temperature increases in the next 50 years are well within this range. Pacific halibut that are recruited to the southern part of their range are juveniles that reared farther north. Unfortunately, the details of the recruitment of these juveniles into the area off British Columbia remains poorly understood.

Halibut stocks are currently at historic high abundances, in part because of the favourable ocean conditions from the late 1970s through to the late 1980s, and in part because of an error in the stock assessment that resulted in an underestimate of the total biomass. Because halibut are widely distributed as adults, it is probable that the effect of climate–ocean related changes is during the larval stage. Pacific halibut are now recognized to live to 55 years, although most fish in the fishery range in age from about 10 to 20 years. The existence of older fish in the population may indicate that over evolutionary time Pacific halibut experienced prolonged periods of poor recruitment. Therefore, future periods of poor recruitment should be expected. If, in the future, areas need to be closed to protect spawning stocks, there would need to be an agreement between Canada and the United States as both countries share the responsibility for conservation of this species. The fishery is managed by the IPHC which allows a percentage of the total biomass to be fished. As declines occur, the catch is reduced. At a minimum spawning biomass, no fishing would be allowed. The population is therefore protected from overfishing.

As for most species, the mechanisms that affect marine survival are unknown. Thus it is not possible to interpret specific environmental changes, even if such changes could be forecasted. In general, however, it is believed that strong onshore flows, resulting from strong northward flowing currents, are favourable for reproduction. A concern is that there could be a weakening of winds that could affect both the amount of onshore transport as well as the food required for the larval and young juveniles. If the impacts of global warming weaken onshore transport and reduce productivity, then halibut year-class survival may be poor, and there may be prolonged periods of poor recruitment.

In recent years, the percentage of the biomass in the southern portion of the range has decreased relative to the biomass in the mid-portion. The reasons for the change are unknown, but could be an indication that halibut recruiting to the southern areas no longer moves as far south.

The impact of climate change on halibut off British Columbia is most important at the larval and juvenile fish stage. As the year-class strength probably is determined at this stage and most larval and juvenile halibut are found in ecosystems north of Canada, it will be the conditions in the Gulf of Alaska, and perhaps the Bering Sea, that are most influential. The major factor affecting future production of the population appears to be the changes in the PDO or Aleutian Low. If there is a strengthening as predicted by Mote *et al.* (1999) and Salanthé (2006), it is possible that changes might improve productivity, at least in the short-term. However, fewer of these recruiting fish may migrate south into the Canadian zone. Production in recent years has been at historic high levels. Thus, any increases in the strength of the Aleutian Low would continue production at these high levels. If production of the population remained high on average, but southward migration was reduced, how would this affect the fishing quotas? If the adults at the southern limit of their distribution contribute much less to the total production than fish spawning farther north, should the exploitation rate be constant for all areas? It is probable that one consequence of greenhouse gas-induced climate change will be a requirement to re-negotiate existing fishing agreements with the United States.

Pacific ocean perch

Pacific ocean perch appear to respond to climate variability at the regime scale; however, given their late age at maturity, recruitment success or failure is not evident until long after year-class strength has been determined. It is noteworthy that the abundance of Pacific ocean perch (and other slope rockfish) abundance has increased steadily or remained stable since the late 1980s (Richards *et al.*, 1997), as a result of very strong year classes in 1976, 1980 and 1984, and average year classes in the early and mid-1980s. These strong year classes began recruiting to the fishery in the late 1980s. The high abundance of these stocks in the current regime is a reflection of the productivity in the 1977–1988 regime, a pattern similar to that described earlier for halibut. The inability to evaluate recruitment in time to make immediate changes to a fishery indicates that this species (and other rockfish with similar life histories) will likely be overfished if regime shifts occur more frequently. The most appropriate management adaptation may be to reduce exploitation rates, and to ensure that some habitat is restricted to fishing. More frequent and more extreme shifts in the Aleutian Low or PDO will introduce more variability in the recruitment of Pacific ocean perch, and there will be more periods like that of 1977–1989 and less of the conditions typical of the 1947–1976 period. With effective management, it is possible that there could be more frequent strong year classes.

Pacific sardine

We know from the studies of Kawasaki (1991) that fluctuations in the abundance of sardines are synchronous around the North and South Pacific Ocean. We also know that around Japan there have been major fluctuations in sardine abundance for centuries (Beamish *et al.*, 1999). Although the exact mechanism or mechanisms that cause these fluctuations are not clearly understood, it is clear that fishing effects are only marginally involved. Climate change and the associated changes in the ocean alter the conditions for successful reproduction in such a way that populations expand and contract rapidly on decadal scales. These expansions and contractions occur quickly, confirming that climate impacts have profound and rapid effects on the structure of large marine ecosystems.

The sardines that occur off British Columbia are produced to the south, off the coasts of California and Mexico. There is some spawning off British Columbia, but it is minor. We know that the period prior to 1947 was favourable for Pacific sardine production, and that the regime from 1948 to 1976 was not favourable. The sardine population increased off California from 1977 through to the early 1990s, indicating that periods of intense Aleutian Lows (positive PDO and stormy winters) resulted in improved sardine production. If greenhouse gas-induced climate change will increase the frequency of periods of intense Aleutian Lows and increased mid-ocean, winter upwelling (Mote *et al.*, 1999), then sardine population fluctuations should continue, possibly with more frequent favourable periods. Off British Columbia, sardines will still fluctuate in abundance, but warmer coastal waters may result in greater abundances, possibly with resident populations being established. However, periods of collapse will still occur.

Pacific cod

Projections of temperature changes are for surface waters and ocean temperatures to change slower than land temperatures. However, in the late 1990s, bottom temperatures in March in the Strait of Georgia were approximately 9.3°C. Thus, it is apparent that several degrees of warming will change the southern limit of Pacific cod distribution, and will, perhaps, move it as far north as southern Alaska. Pacific cod recruitment is therefore a sensitive indicator of ocean changes affecting groundfish. It is predicted that they will gradually disappear from the Strait of Georgia and off the west coast of Vancouver Island as bottom temperatures warm.

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The Fishery

Seafood has always been a significant part of the Japanese diet and today accounts for about 40% of the protein consumed by Japanese people. Domestic marine fisheries are generally divided into coastal fisheries, offshore fisheries, and distant-water fisheries (Table 9). From 1972 to 1988, Japan had the world's largest fisheries. Catches increased through to 1984 with the maximum production of 12,820,000 t. The total catch of all marine species declined from the maximum in 1984 to 3,734,209 t in 2000 (Fig. 17). This was a change from 16.0% of the world's catch in 1984, to 5.1% in 2000. In recent years, the fishery in China reportedly exceeds Japanese production. At present, Japan is the largest importer of fish products in the world. Approximately one third of the world catch in weight is exported, and Japan imports about 15% in weight, or one quarter in value, of all exported fish products. The decline in catch in recent years (Fig. 17) is related to the natural decline in Japanese sardine abundance in the 1990s and the reduced catches in distant-water fisheries (Table 9, Fig. 18).

Climate and Ocean Influences

A major influence on the production of fish in the Japanese coastal and offshore fisheries is the structure and dynamics of the subarctic current, the Oyashio, the subtropical currents, the Kuroshio and Tsushima, and the transition area between the Oyashio and Kuroshio (Fig. 19). The changes in currents affect vertical mixing, which alters the supply of nutrients to the surface production zone, as well as migration and larvae transportation. Changes in nutrient supply affect primary production which, in turn, changes the abundance and species of zooplankton which are the principal food of fishes. Mechanistic linkages between climate and physical oceanographic changes and stock productivity generally occur through bottom-up scenarios. In the Oyashio area, the major feeding grounds of sardine, chub mackerel, saury, common squid, and many other species, zooplankton density since the 1970s has been negatively correlated with sardine biomass; other processes controlling the sardine population may be occurring (Taniguchi, 1999). Chiba *et al.* (2004) concluded that annual production of copepods

Table 9 Japanese domestic fishery production.

	Percentage of total					
	1975	1980	1985	1990	1995	2000
Distant water fisheries	31	20	18	14	13	14
Offshore fisheries	43	52	54	56	45	41
Coastal fisheries*	26	28	28	30	43	45
Total (in 1,000 t)	10,346	10,900	11,965	10,843	7,322	6,252

Source: Japan Ministry of Agriculture, Forestry, and Fisheries,
* including capture fisheries and aquaculture

since the 1960s, along the “PH line” (41°30′N, 142°E–147°E), representing the Oyashio, has decreased because of the attenuation of winter mixing.

The biomass of large- and small-sized copepods from 1971 to 1989 in Kuroshio area was affected by Kuroshio meandering and winter solar radiation, respectively (Nakata *et al.*, 2001). The composition of zooplankton size and timing of the spring bloom in Tsushima, Kuroshio, and Kuroshio Extension would have significant effects on survival and growth of juvenile fishes, and thus on recruitment. The observed species replacements among small pelagics may be partly explained by such differences in availability of suitable zooplankton. The period of the large Kuroshio meandering, called “A-type”, coincided with that of an intensified subtropical gyre and westerly winds. In the northwestern area of the subtropical gyre, intensification of wind speed and destratification of surface waters generally result in a decrease of zooplankton biomass (Sugimoto and Tadokoro, 1998). The mixed layer depth during the positive Pacific Decadal Oscillation (PDO) period (1977–1988) was 30 to 80% deeper than the negative PDO period (1960–1976) in the subtropical and transition areas of the North Pacific, whereas the mixed layer depth was 20 to 30% shallower in the subarctic area (Polovina *et al.*, 1995). During the positive PDO period, zooplankton production is considered to increase by enhanced nutrient supply in the subtropical area (Taniguchi, 1999). Polovina *et al.* (1995) observed that the mixed layer depth in the Oyashio area was approximately 10% deeper during 1977–1988 relative to the 1960–1976 level. The decadal change in mixed layer depth did not significantly affect the declining trend in lower trophic level production in the Oyashio area (Chiba *et al.*, 2004). Therefore, the effects of greenhouse gas production on water density and salinity may be more significant for low trophic production in the Oyashio area than in the PDO-related mixed layer depth.

If winds are reduced by future warming of the ocean, the primary production in the seas around Japan may be reduced because of reduced vertical mixing in winter. Warming could also reduce the nutrient supply to the subarctic gyre and thus decrease primary production in the Oyashio region. However, variation in zooplankton biomass off Sanriku had a positive correlation with sea surface temperature (SST) and sunshine at Nemuro and a negative correlation with sea level pressure at Nemuro in the Oyashio (Fig. 20, Tomosada and Odate, 1995). Thus, higher SST and stormier conditions would improve productivity, although low zooplankton biomass in the Oyashio, Kuroshio and transition waters during the 1980s may have been caused by mass predation by Japanese sardine (Taniguchi, 1999). In general, the impacts of climate and ocean changes vary among areas and species, and the impacts are poorly understood, but it is clear that climate and ocean conditions are major influences in the production of fishes in the seas around Japan.

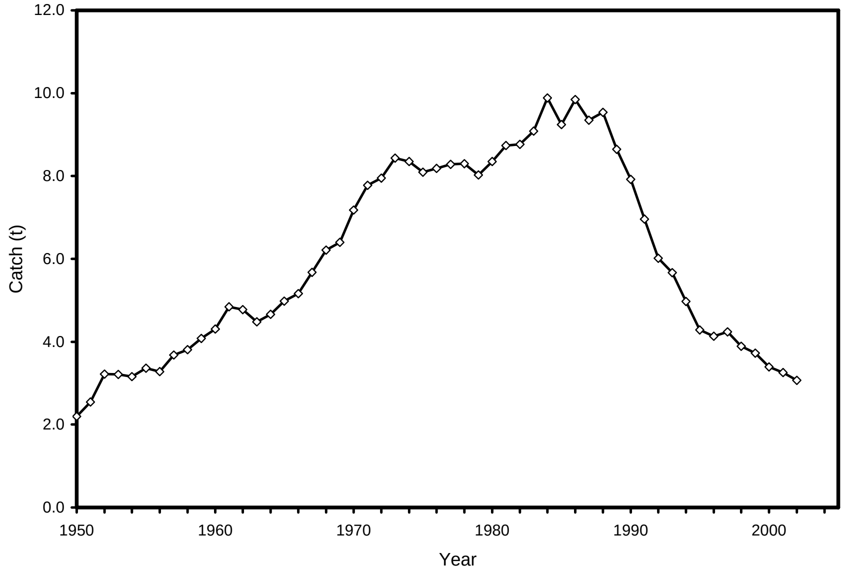


Fig. 17 Total marine catch by Japan from 1950 to 2002 (FAO data).

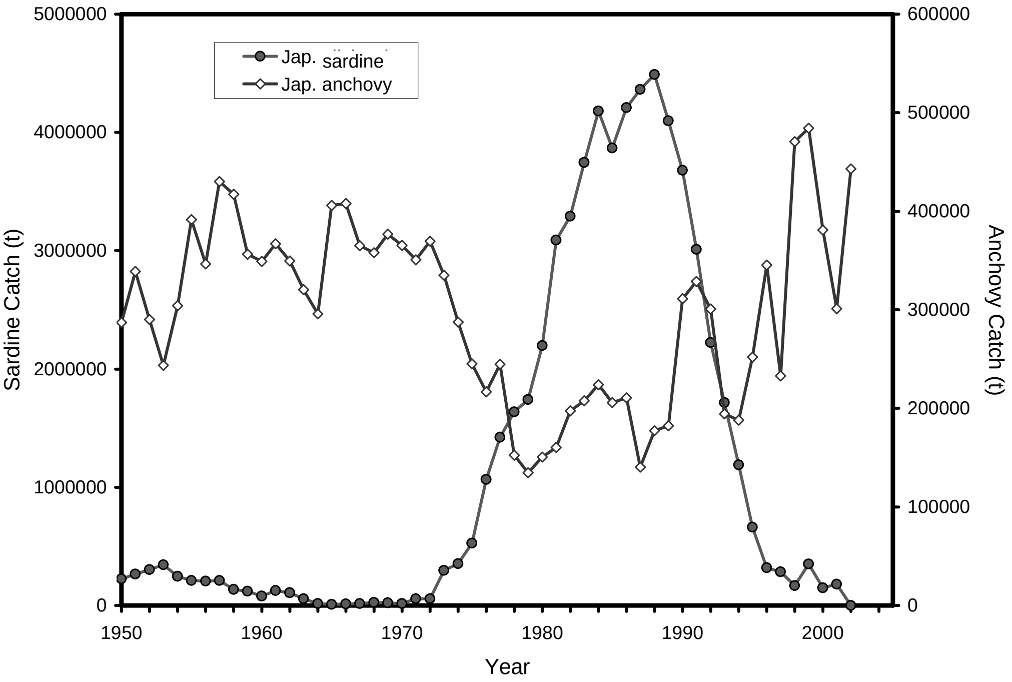


Fig. 18 Japanese sardine and anchovy catch by Japan from 1950 to 2002 (FAO data).

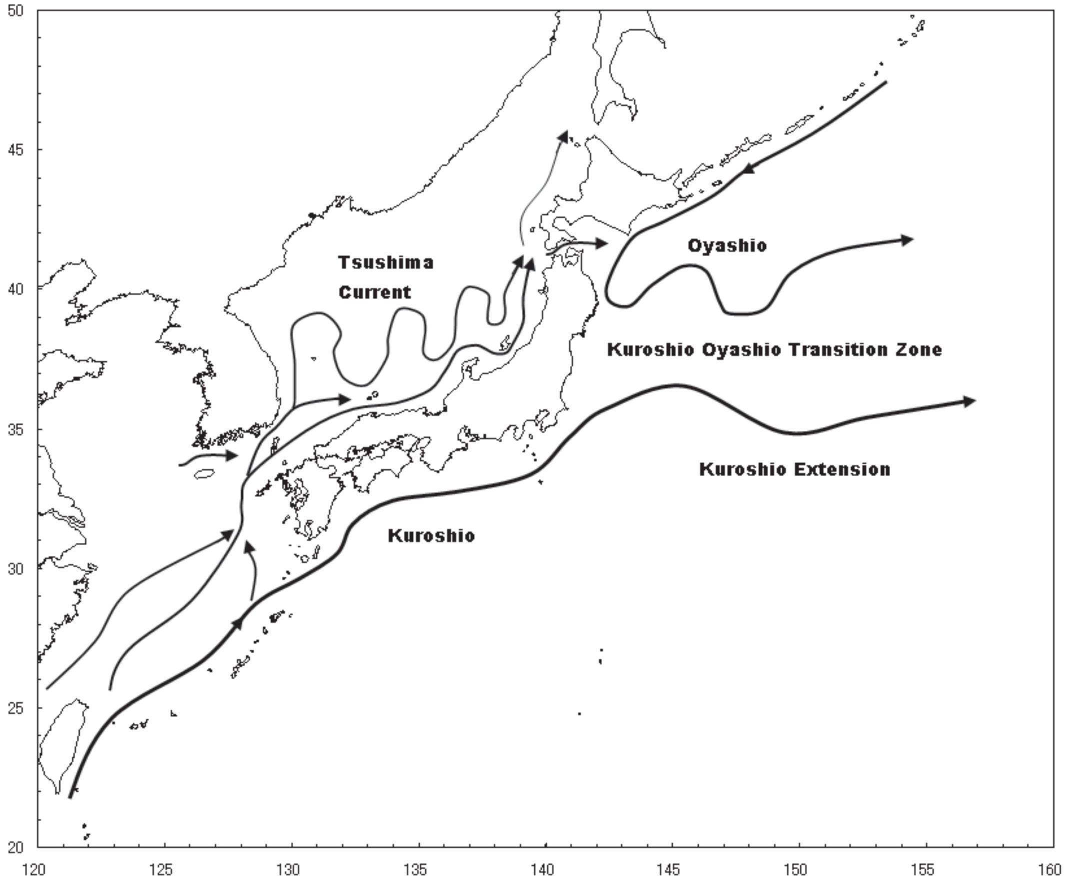


Fig. 19 Major ocean current systems around Japan.

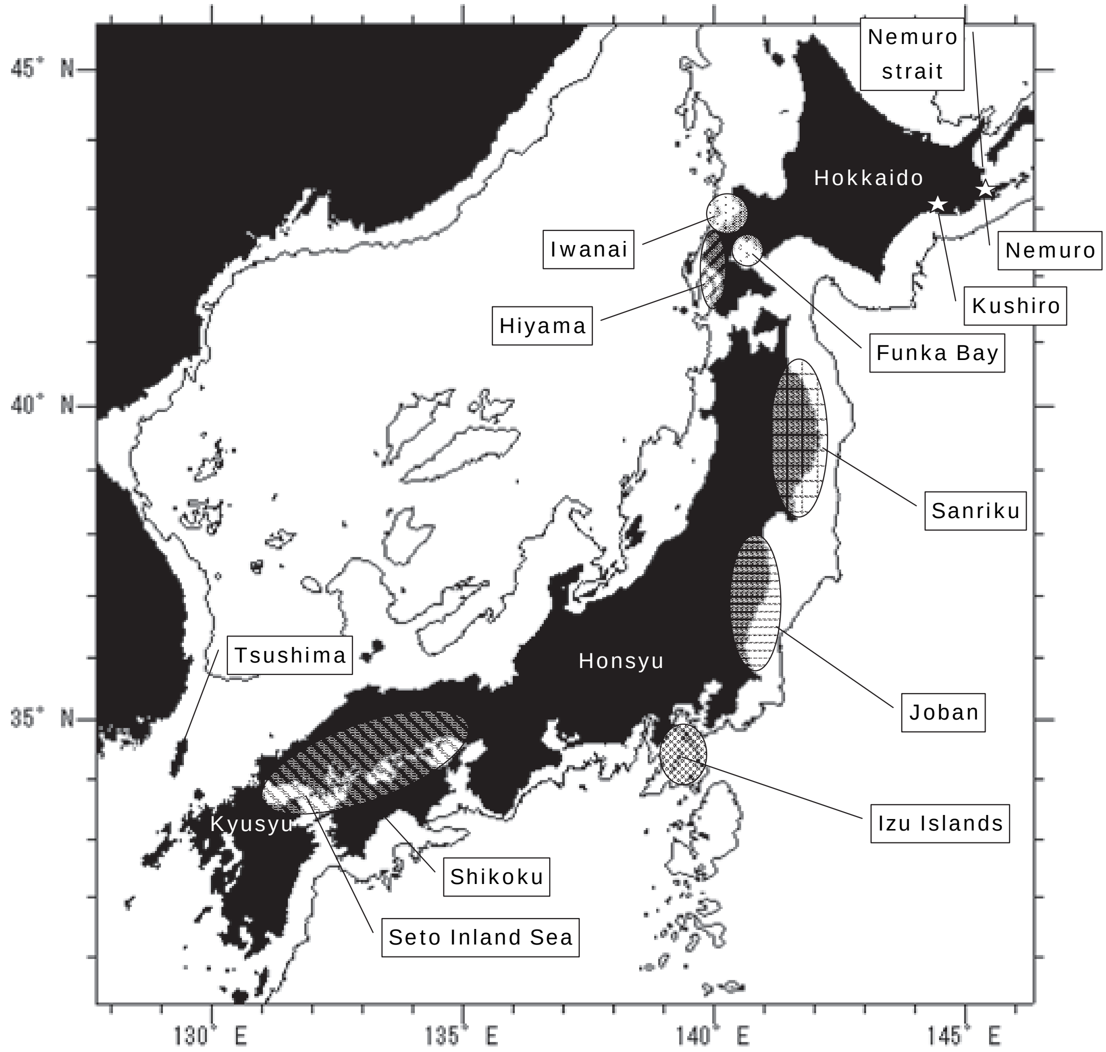


Fig. 20 Map showing key locations (cross-hatched ovals, and stars) and islands mentioned in the text, and 1000 m isobath around Japan.

Key Species in the Fishery

In our report, a stock is considered to be an aggregation of individuals that are fished as one unit. The definition does not imply that there are genetic differences among stocks. A population is a large aggregation of individuals or stocks that have discrete migration patterns, spawning areas and/or spawning seasons, although there may be migrations of individuals among populations. In this study we consider the impacts of climate and climate change on nine species (Table 10) that represented approximately 58 to 80% of the total catch between 1980 and 2000. Biomass and indices of production rates of selected stocks are shown in Figs. 21–24.

Chub mackerel (*Scomber japonicus*)

Biology

Chub mackerel mature mostly at an age of 2 years and a fork length of 32 cm (Yatsu *et al.*, 2002; Watanabe and Yatsu, 2004). Spawning occurs during winter and spring in the area around the Izu Islands (Fig. 20), East China Sea and southern Japan Sea. The Oyashio Current is a major feeding and rearing area in the Pacific Ocean. The fisheries for chub mackerel target a wide range of size, including immature fish, which have been heavily fished since the 1990s. They feed on zooplankton, squids and fishes, particularly anchovy.

Table 10 Catches of key species and their combined percentage of the total catch in t (FAO).

	1980	**1985**	**1990**	**1995**	**2000**
Chub mackerel	1,300,994	771,764	272,477	469,447	346,220
Jack mackerel	56,177	158,073	227,837	317,993	249,040
Japanese sardine	2,197,744	3,866,928	3,678,229	661,391	149,616
Anchovy	150,604	205,824	311,427	251,958	381,020
Alaska (walleye) pollock	1,552,429	1,533,179	871,408	338,507	300,001
Chum salmon	87,713	167,960	207,989	249,982	151,123
Pacific saury	187,155	245,944	308,271	273,510	216,471
Common squid*	330,464	132,519	209,390	290,273	337,285
Neon flying squid**	552,722	462,044	549,410	435,772	28,271
Total	6,416,002	7,544,235	6,636,438	3,288,833	2,159,047
% of all species	75.42%	79.50%	80.19%	69.83%	57.81%

Source: FAO.
* referred to as "Japanese flying squid" in FAO statistics,
** after Yatsu *et al.* (2000)

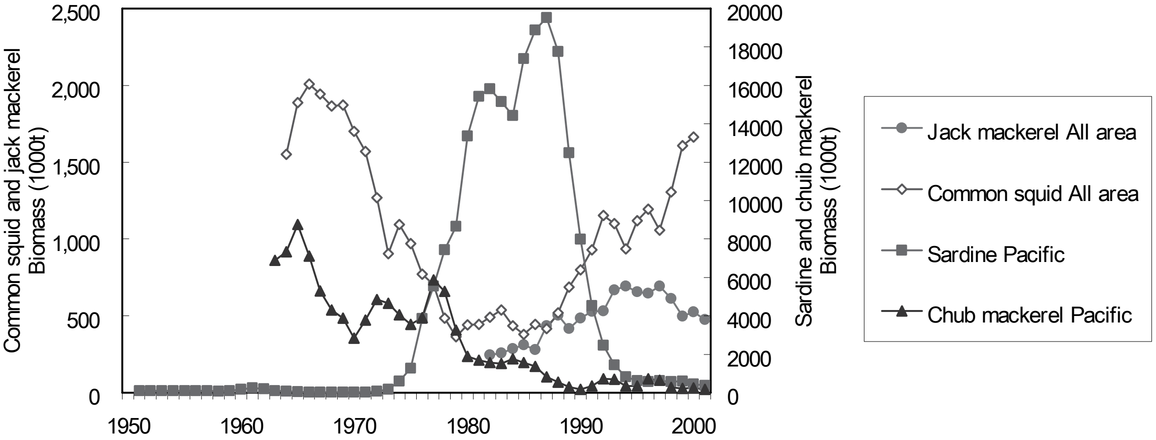


Fig. 21 Biomass of Japanese sardine (Pacific stock), chub mackerel (Pacific stock), jack mackerel (two stocks combined) and common squid (two stocks combined).

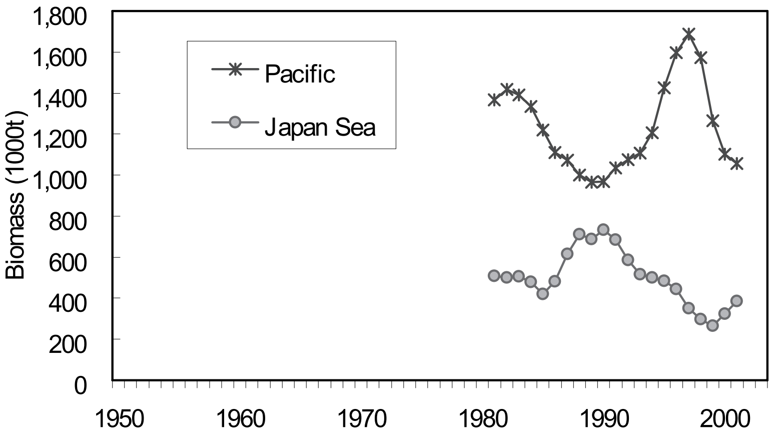


Fig. 22 Biomass of the Pacific stock and the northern Japan Sea stock of walleye pollock.

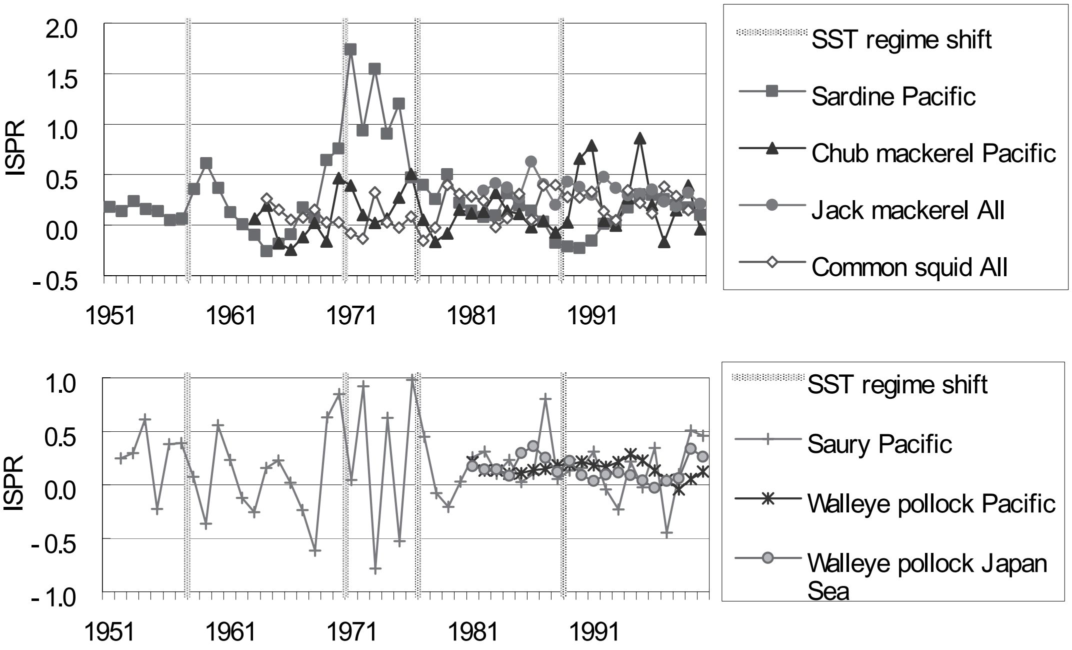


Fig. 23 Trajectories of instant surplus production rates (ISPR) of seven stocks around Japan. Years of SST (sea surface temperature) regime shifts follow Yasunaka and Hanawa (2002).

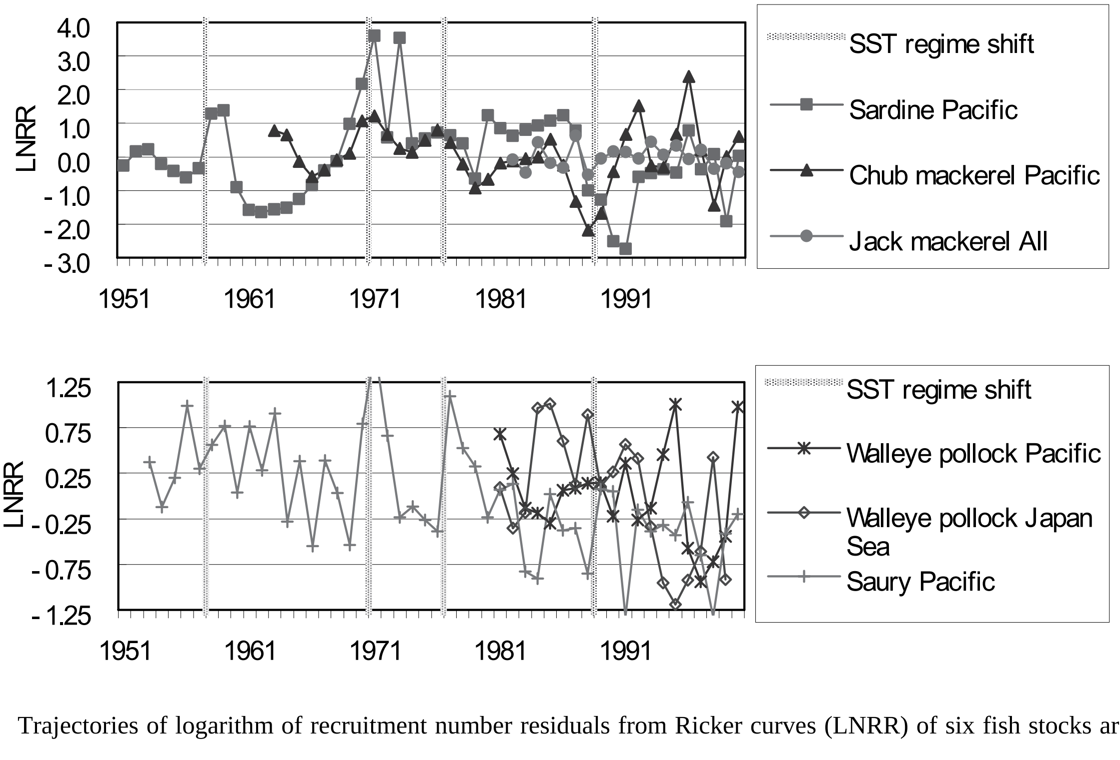


Fig. 24 Trajectories of logarithm of recruitment number residuals from Ricker curves (LNRR) of six fish stocks around Japan.

Fishery

Two stocks, the Tsushima Current stock and the Pacific stock, contribute to the catch. The Tsushima Current stock is distributed in the East China Sea, Yellow Sea, Bohai Sea, and the Japan Sea (Fig. 19). The Pacific stock is distributed along the Pacific coast of Japan and east to the Central North Pacific Ocean, including inside of the Exclusive Economic Zone (EEZ) of Russia (Belyaev and Ivanov, 1987). Migration between the Pacific stock and the Tsushima Current stock has been reported, but is believed to be rare.

Climate and ocean effects

Productivity of the Pacific stock was high in the early 1970s (Figs. 23 and 24) and catches were high in the 1980s when the PDO was generally negative (Table 11). The productivity tends to be similar to that of the Japanese sardine and Pacific saury. After the 1989 regime shift, chub mackerel did not recover, possibly as a consequence of the extensive fishing effort, especially for immature fish (Yatsu *et al.*, 2002). Productivity of the Pacific stock was negatively related to the PDO without a lag (Fig. 25). The biomass of the Pacific stock of chub mackerel appears to be negatively related to PDO with a 1-year lag (Fig. 26) and SST of the northern Izu Islands in winter within the Kuroshio, which suggests that there is a relationship between SST and spawning success (Yatsu *et al.*, 2005). There was a distinct reduction in production (and catch) following the 1977 regime shift of the PDO to a positive state indicating that decadal-scale variability affects recruitment. Sardine biomass also negatively affected the reproductive success of the Pacific stock of chub mackerel due to possible competition for prey during the larval stage (Yatsu *et al.*, 2005).

Table 11 Chub mackerel catches (t).

Year	Catch (FAO)	Catch, Tsushima Current stock	Catch, Pacific stock
1980	1,300,994	504,000	617,000
1981	907,589	470,000	393,000
1982	717,513	402,000	293,000
1983	804,479	408,000	353,000
1984	813,262[1]	353,000	527,000
1985	717,764	305,000	403,000
1986	944,350	344,000	587,000
1987	700,686	329,000	299,000
1988	646,196[1]	411,000	248,000
1989	526,270[1]	414,000	121,000
1990	272,477	207,000	20,000
1991	253,991	220,000	24,000
1992	266,609[1]	234,000	88,000
1993	664,298[1]	373,000	401,000
1994	633,062	503,000	119,000
1995	469,447[1]	364,000	152,000
1996	760,430[1]	740,000	261,000
1997	848,967	337,000	343,000
1998	511,238	297,000	111,000
1999	381,866	242,000	61,000
2000	346,220	200,000	89,000

[1] FAO catch is smaller than sum of the two stocks.
Source of catch by stock: FAJ (2004a)

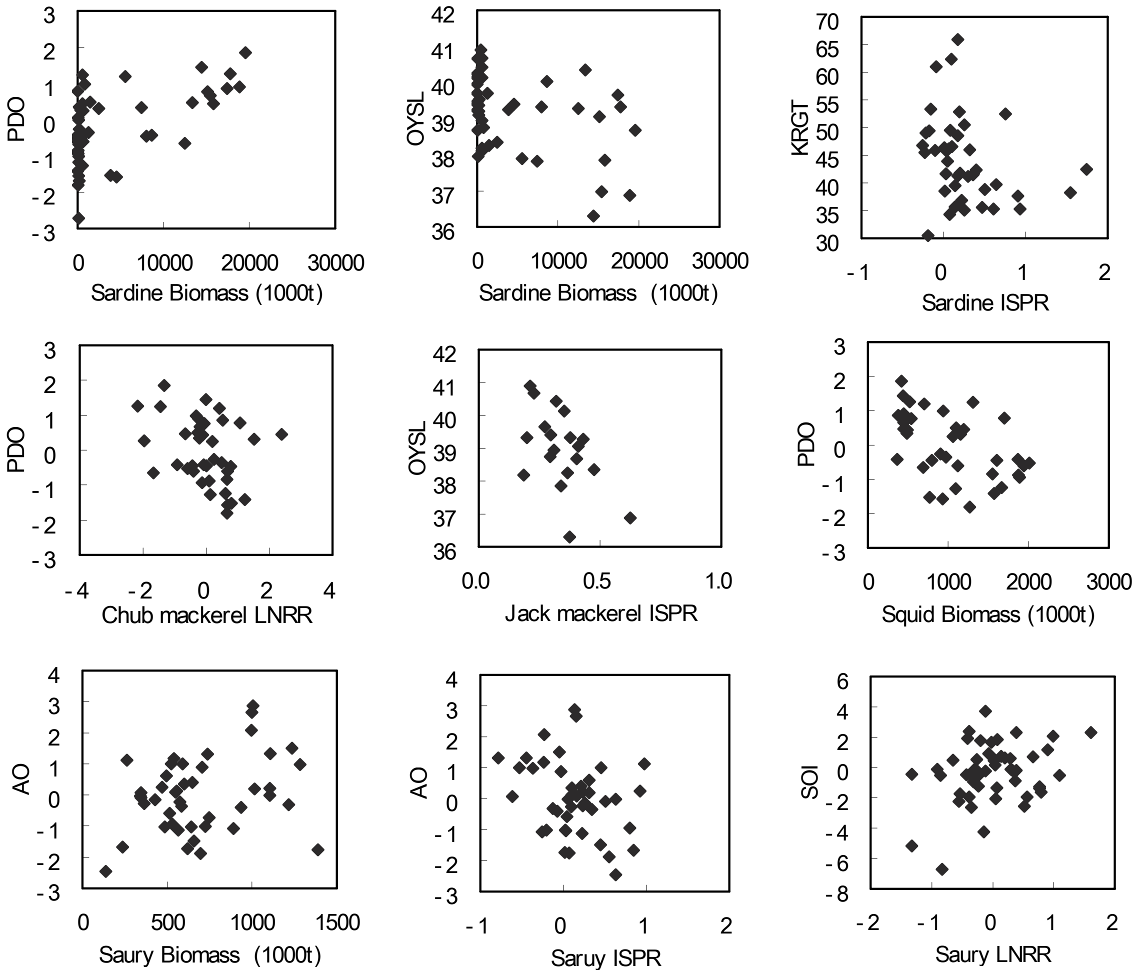


Fig. 25 Statistically significant relationships between productivity of stocks and environmental variables with no time lag. KRGT: Kuroshio geostrophic transport across 134ºE in winter, OYSL: southern limit of the coastal branch of the Oyashio Current (adopted from Yatsu *et al.*, 2005).

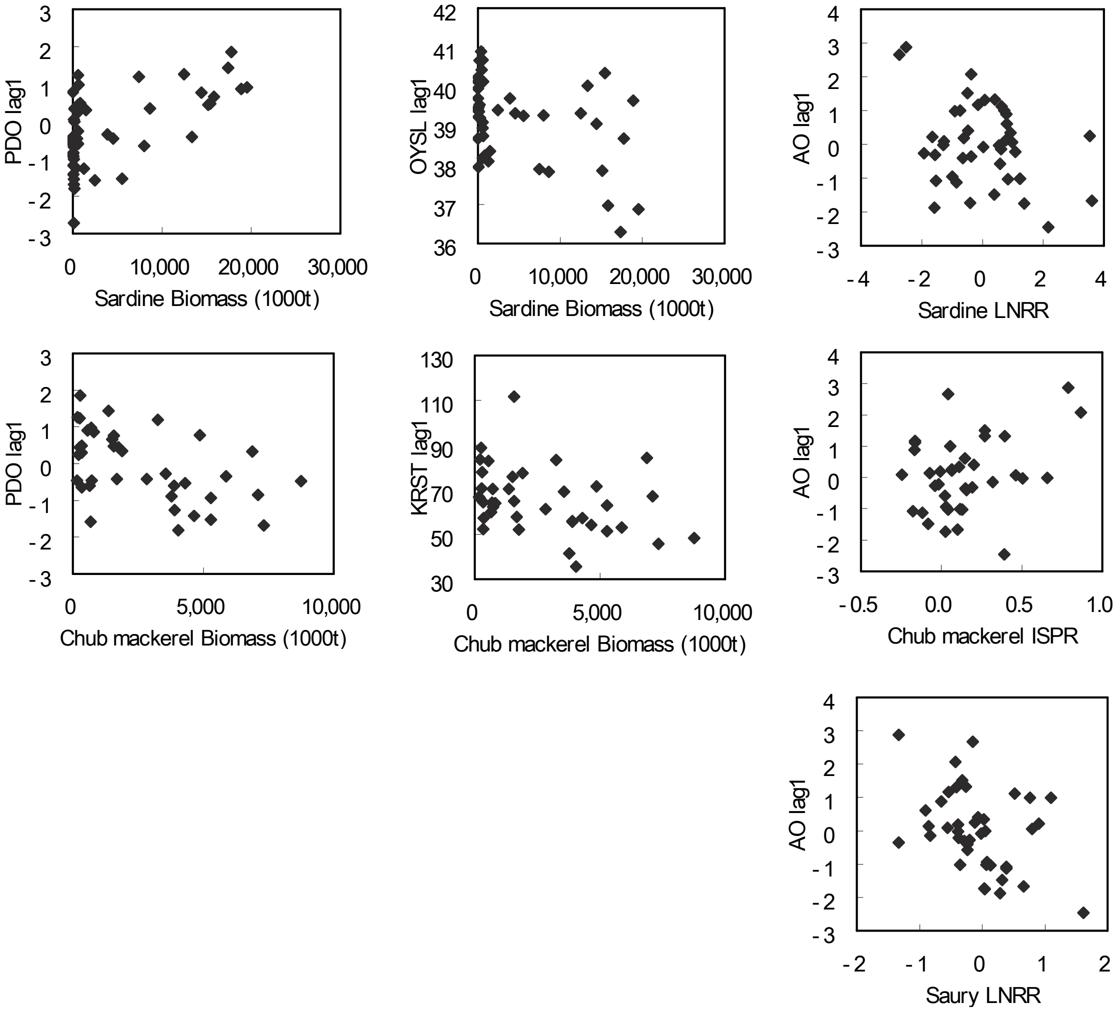


Fig. 26 Statistically significant relationships between productivity of stocks and environmental variables with a 1-year time lag. KRST: Kuroshio Sverdrup transport along 30ºN in winter, OYSL: southern limit of the coastal branch of the Oyashio Current (adopted from Yatsu *et al.*, 2005).

Jack mackerel (*Trachurus japonicus*)

Biology

Jack mackerel mature at age 1 at a fork length of about 20 cm. Maximum age is 5 years and maximum size is about 45 cm. They tend to change their habitat from pelagic to near-bottom as they grow. Jack mackerel are basically zooplankton feeders.

Fishery

Purse seines and set nets are the major methods of fishing. Total catches mostly increased in the late 1980s and remained high until 1999 (Table 12).

Two stocks have been recognized for stock assessments: the Pacific stock and the Tsushima Current stock. The Pacific stock is distributed along the Pacific coast of Japan at about 145°E longitude and north to about 40°N latitude. The Tsushima Current stock is distributed in the East China Sea and southern Japan Sea.

Several tagging experiments and biological surveys have been conducted to study stock structure. Earlier, the Tsushima Current stock was divided into more than three stocks, but now it is treated as a single stock for assessments. It is believed that both stocks overlap at the southern coast of Japan off Kyushu Island and have common spawning grounds in the East China Sea. A new research project

Table 12 Jack mackerel catches (t).

Year	Catch (FAO)	Tsushima Current stock, Japan	Tsushima Current stock, Korea	Tsushima Current stock, Total	Pacific stock, Japan
1980	56,177	39,000	1,000	40,000	11,000
1981	66,044	46,000	6,000	52,000	12,000
1982	108,754	87,000	11,000	98,000	13,000
1983	134,535	103,000	12,000	115,000	18,000
1984	139,435	111,000	7,000	118,000	17,000
1985	158,073	132,000	16,000	148,000	14,000
1986	114,581	68,000	7,000	75,000	37,000
1987	186,979	139,000	14,000	153,000	37,000
1988	234,225	184,000	40,000	224,000	30,000
1989	188,111	140,000	23,000	163,000	33,000
1990	227,837	170,000	17,000	187,000	42,000
1991	228,894	153,000	16,000	169,000	61,000
1992	230,573	153,000	28,000	181,000	62,000
1993	318,403	226,000	38,000	264,000	79,000
1994	332,264	235,000	38,000	273,000	80,000
1995	317,993	231,000	12,000	243,000	70,000
1996	334,275	195,000	15,000	210,000	80,000
1997	326,668	233,000	23,000	256,000	76,000
1998	314,723	224,000	22,000	246,000	60,000
1999	214,129	141,000	14,000	155,000	48,000
2000	249,040	147,000	20,000	167,000	56,000
2001	217,742	–	–	–	–
2002	199,495	–	–	–	–

Source of catch by stock: FAJ (2004a)

on jack mackerel is using population genetics methods and models of larval transport to help determine the degree of overlapping distributions. The Tsushima Current stock extends into the Korean and Chinese waters beyond the Japanese EEZ.

Both stocks have separate spawning grounds along the coast, but the common spawning area is in the East China Sea, located from 25° to 30°N. The SST range at the spawning grounds is from 15° to 26°C (optimum 16°–17°C). The SST in the fishing area is from 24° to 29°C.

Climate and ocean effects

The biomass of jack mackerel (both stocks combined) is positively correlated with winter SSTs of the Japan Sea, East China Sea and Pacific coast of southern Japan. On the other hand, jack mackerel productivity and recruitment improved when the spring SST was lower in the East China Sea where major spawning occurs (Sassa and Konishi, 2002). Productivity appears to have been affected by the 1988/89 regime shift (Figs. 23 and 24), although earlier shifts did not appear to have major impacts. There seems to be a negative relationship with PDO, in which the periods of positive PDO resulted in reduced productivity. Thus, in the 1980s, catches were less than in the 1990s (Table 12).

Japanese sardine (*Sardinops melanostictus*)

Biology

Japanese sardines mature at 17 cm in standard body length and the first age of maturation is 1 year during a low stock period and 3 years during a high stock period (Morimoto, 1998). The species is recruited to the fishery at the age of about 6 months when commercial fisheries harvest Japanese sardines in the size range of 11 to 24 cm. However, post-larvae individuals (whitebait or shirasu) are also fished during high stock abundance periods. Maximum age is about 7 years and maximum lengths are approximately 25 cm. Prey of sardine includes both zooplankton and phytoplankton, the latter of which is seldom utilized by other fishes.

Two stocks of Japanese sardine have been recognized. The Pacific stock and the Tsushima Current stock are distinguished by their distributions and migration patterns. The Pacific stock is distributed along the Pacific coast of Japan and east to 180° longitude during high abundance periods. In periods of low abundance, only juveniles migrate into the Central North Pacific. The western boundary of the Pacific stock coincides with the spawning areas from the eastern coast to Kyushu Island (Fig. 20) to northern Japan at high abundances. In low abundances, the spawning area of the Pacific stock is the southern coast of Shikoku Island and central Japan. Feeding areas are mainly in the Oyashio and Kuroshio–Oyashio Transition Zone (KOTZ) in the summer and autumn. The Pacific stock occurs in the EEZ of Russia and outside of the EEZ of Japan. The Tsushima Current stock is distributed in the East China Sea and the Japan Sea. The major spawning area is in the East China Sea and the southern part of the Japan Sea during the high stock period, but it shrinks to the East China Sea during the low abundance. The northern limit of their migration also shrinks from the Sakhalin waters and Okhotsk Sea to the southern part of the Japan Sea (Hiyama, 1998). There are no apparent genetic differences between the two stocks (Okazaki *et al.*, 1996).

Fishery

Japanese sardines have a long history of large fluctuations in abundance (Table 13, Figs. 18 and 21). Kawasaki (1983) was the first to recognize that the fluctuations in sardine abundance were synchronous with sardine populations off the Pacific coast of North America and Chile. Off Japan, the catches in the 1960s were about 10,000 t annually. In the mid-1970s the catches by Japan (and abundances) increased dramatically to about 4 million t per year in the mid-1980s. In the early 1990s, catches (and abundances) decreased quickly to levels of less than 200,000 t in 2000 (Table 13).

Climate and ocean effects

The large fluctuations in abundance have been shown to relate to large-scale climate changes and not to unique local environmental conditions or to fishing (Figs. 25 and 26; Kawasaki, 1983). Large-scale or global climate change causes a strengthening or weakening of winds and ocean currents off the coast of Japan which affects the upwelling of nutrients and plankton production and larvae transportation (Kasai *et al.*, 1997). There is a relationship between the winter SST or subsurface temperature in the rearing area of juvenile sardines and their survival for both stocks (Hiyama *et al.*, 1995; Ebisawa and Kinoshita, 1998; Noto and Yasuda, 1999). The ocean conditions, in turn, are related to direct atmospheric forcing on a decadal scale, as identified by the PDO and the boundaries of the Oyashio and Kuroshio Currents (Yatsu *et al.*, 2005).

There are a number of studies on the impact of ocean conditions on the population dynamics of the Japanese sardine, as the fishery is important economically and socially to the Japanese people. Watanabe *et al.* (1995) showed that mortality after the end of the first-feeding stage, *i.e.*, from post-larva to age 1, controlled year-class strength. Hiyama *et al.* (1995) reported that both density-dependent effects and winter temperature of the western Japan Sea at 50 m depth are responsible for the reproductive success of the Tsushima Current stock. On the basis of a numerical model, Kasai *et al.* (1997) concluded that strong year classes of sardine can be formed by intensive transport of larvae to the Kuroshio Extension and by good survival in the KOTZ where nutrient supply is affected by the strength of the Oyashio. This conclusion was supported by Ebisawa and Kinoshita (1998) who detected a negative correlation between reproductive success of the Pacific stock and Oyashio expansion (represented by an area of SST < 10°C) in the Joban area (Fig. 20). Thus, the more southern intrusion of the Oyashio coastal branch would enhance zooplankton production in the nursery ground of the KOTZ which supports survival of juveniles derived from spawning grounds formed offshore of Shikoku and Kyushu beyond the Kuroshio axis. Noto and Yasuda (1999) showed that low SST in the southern

Table 13 Japanese sardine catches and estimated biomass (t).

Year	Catch (FAO)	Catch, Pacific stock	Catch, Tsushima stock
1980	2,197,744	1,679,000	–
1981	3,089,311	2,460,000	–
1982	3,289,954	3,037,000	–
1983	3,745,148	3,495,000	–
1984	4,179,426	3,786,000	–
1985	3,866,928	3,356,000	–
1986	4,209,513	3,766,000	–
1987	4,362,025	3,314,000	–
1988	4,488,411	3,446,000	–
1989	4,098,989	2,849,000	1,586,000
1990	3,678,229	2,525,000	1,521,000
1991	3,010,498	1,948,000	1,294,000
1992	2,223,766	1,151,000	989,000
1993	1,713,687	729,000	923,000
1994	1,188,848	416,000	765,000
1995	661,391	262,000	340,000
1996	319,354	153,000	143,000
1997	284,054	230,000	37,000
1998	167,073	136,000	32,000
1999	351,207	295,000	54,000
2000	149,616	130,000	15,000

Source of catch by stock: FAJ (2004a)

region of the Kuroshio Extension improved food production for larval sardines and resulted in improved year-class strength of the Pacific stock. When the southern region of the Kuroshio Extension is favorable for sardine survival, they are able to expand their adult distribution and their spawning areas. A low SST is an index of mixed layer depth (Polovina *et al.*, 1995). In subtropical waters, including the Kuroshio, deeper mixing layers contain more nutrients in the spring and thus more productive habitat for juvenile sardines. Conversely, warmer SSTs reduce productive habitat, and were shown to be related to high larval mortality. If unfavorable conditions persist for more than 7 years, the life span of the Japanese sardine, the population that migrates over a wide area would collapse. Recent studies revealed that SST directly affects growth rates of larvae and juveniles, hence early survival rates (Takahashi *et al.*, 2004; Takasuka *et al.*, 2004). The coastal population would remain, but would be small as the coastal habitat suitable for production is limited. Noto and Yasuda (1999) suggested that the abrupt increase in SST in 1988 in the southern region of the Kuroshio Extension indicated a close relationship between decadal-scale climate changes and ocean changes, and the dramatic fluctuations in abundance.

Anchovy (*Engraulis japonicus*)

Biology

Anchovy mature at a standard body length of about 6 cm in coastal waters and at about 10 cm in offshore and oceanic waters. Age and growth of Japanese anchovy are controversial, and growth may greatly fluctuate, depending on prey conditions and migration routes. Annual rings in scales suggest slower growth (10 cm at 1 year, 14 cm at about 2 years) in contrast to much faster growth estimated by daily increments in otoliths (the age of 12 to 13 cm fish was 263 to 295 days) (Mitani, 2001). Recruitment into the fishery occurs at about the age of a few months (whitebait or shirasu) and the maximum age is about 3 years at a length of 14 cm, according to traditional age estimation with scales. Anchovy are zooplankton feeders.

Fishery

Three stocks are recognized for stock assessment: the Pacific stock, the Seto Inland Sea stock, and the Tsushima Current stock. The boundaries among stocks are not always clear, especially during periods of large abundances as mixing and exchange sometimes occur, depending on their densities. The Tsushima Current stock expands into the Russian, Korean, and Chinese waters, beyond the EEZ of Japan. The Pacific stock is also distributed in Russian EEZ when the stock is abundant.

Anchovy catches averaged 185,691 t between 1980 and 1989, then increased to 311,427 t in 1990, and remained high in the 1990s, averaging 317,290 t between 1990 and 2000 (Table 14). The major fisheries use purse seines and set nets; whitebait or shirasu are harvested by seine nets (a small-scale midwater trawl). The spawning stock biomass was estimated using the procedures of virtual population analysis (VPA) and egg census surveys (FAJ, 2004a) for 1996 to 2000, and shows a major increase beginning in 1998.

Climate and ocean effects

In general, there is an alternating pattern of abundance between anchovy and sardine (Fig. 18). In the 1950s and 1960s, anchovy abundance was large when sardine abundance was small. This pattern switched in the late 1970s and 1980s, reversing again in the 1990s. Recent studies revealed that optimum SST on early growth rates of anchovy are higher than sardine, thus decadal shifts in SST may explain the alternation of sardine and anchovy through selective survival of larger or faster-growing individuals (Takahashi *et al.*, 2004; Takasuka *et al.*, 2004, 2007). It is apparent that the impacts of climate–ocean conditions are opposite for sardines and anchovies.

Table 14 Anchovy catches (t).

Year	Catch (FAO)	Tsushima Current stock, Japan[1] only	Pacific stock	Seto Island Sea stock
1980	150,604	–	–	40,000
1981	160,468	–	–	68,000
1982	197,453	–	–	76,000
1983	207,601	–	–	81,000
1984	224,069	–	–	75,000
1985	205,824	–	–	100,000
1986	210,630	–	66,000	93,000
1987	140,509	–	63,000	36,000
1988	177,492	–	68,000	58,000
1989	182,258	–	88,000	40,000
1990	311,427	–	234,000	32,000
1991	328,870	76,000	207,000	42,000
1992	300,892	84,000	186,000	27,000
1993	194.511	68,000	101,000	25,000
1994	188,034	57,000	110,000	21,000
1995	251,958	95,000	140,000	23,000
1996	345,517	114,000	210,000	20,000
1997	233,113	78,000	134,000	20,000
1998	470,616	140,000	304,000	17,000
1999	484,230	143,000	313,000	23,000
2000	381,020	128,000	210,000	34,000

[1] data exists for Korea, and China, Taiwan; source of catch by stock: FAJ (2004a)

Walleye pollock (*Theragra chalcogramma*)

Biology

Walleye pollock are distributed throughout the water column to the bottom. They mature at about age 3 and 32 cm in standard body length (Keizo Yabuki, Hokkaido National Fisheries Research Institute, unpublished data). There is debate about maximum ages, but there is some agreement that walleye pollock can live up to 33 years (King and McFarlane, 2003). There is a spawning migration from overwintering areas to distinct spawning areas, mainly in Nemuro Strait (Fig. 20), Funka Bay (the Pacific stock) and coastal areas of western Hokkaido and Sakhalin (the North Japan Sea stock). However, the spawning area of the latter stock may have shrunk to the Hiyama and Iwanai districts (Fig. 20), southwestern Hokkaido, in response to stock decline. Eggs and larvae are pelagic and only loosely associated with a particular bottom area. Walleye pollock consume a wide variety of prey, including krill, squids, fishes and demersal crustaceans. Cannibalism is common.

Fishery

Four stocks have been recognized for stock assessments around Japan: the North Japan Sea stock, the Kitami (Okhotsk Sea) stock, the Nemuro stock, and the Pacific stock (Tsuji, 1989). This separation is based on information relating to spatial distribution, tagging, age and growth data, morphometric characteristics, and ecological considerations. The North Japan Sea stock is distributed in the northeastern area of the Japan Sea. The Kitami, or Okhotsk Sea, stock is distributed in the southwestern part of the Okhotsk Sea. The Nemuro stock is found during the spawning season in Nemuro Strait. The Pacific stock is distributed along the Pacific coast of the northeastern part of Honshu, Hokkaido, and south Kuril Islands. Tagging studies carried out in the past 40 years have indicated that fish normally migrate among these four stocks (Yoshida, 1982). Biochemical studies have not revealed genetic differences among the four stocks (Iwata, 1975). All stocks, except the Nemuro stock, have two or more spawning grounds. The stability of the spawning stock units and the characteristics of a stock change with the environment and population abundances (Kyushin *et al.*, 1961; Tsuji, 1978). There are also walleye pollock that are pelagic during the feeding period and spawn with a variety of stocks (Ogata, 1956; Yoshida, 1982). All stocks are also distributed within the Russian EEZ. Catch statistics indicate a constant decline in catch since 1980 (Table 15). However, biomass estimates (Fig. 22) indicate that there was an increase in the 1980s in the North Japan Sea stock, but a decrease in the Pacific stock.

Climate and ocean effects

Figures 23 and 24 show that there is no relationship between walleye pollock productivity and regime shifts, although there were decadal-scale fluctuations in estimated biomass. The productivity of the North Japan Sea stock is positively related to SST in the spawning grounds in the winter. The productivity of the Pacific stock is positively related to SST of southern Hokkaido in winter and spring. It appears that ocean conditions affect productivity and result in trends that are approximately decadal; however, there is no clear relationship with standard large-scale indices of climate. In the Pacific stock, strong year classes were produced in 1981, 1991, 1994, 1995 and 2000 (FAJ, 2004a). Strong year classes of the North Japan Sea stock were observed in 1984, 1985, 1986 and 1988 (FAJ, 2004a). Mechanistic linkages between occurrences of strong year class and environmental conditions remain unknown.

Chum salmon (*Oncorhynchus keta*)

Biology

Chum salmon are anadromous. In Japan, virtually all chum salmon are reared in hatcheries and released after a short rearing period following hatching. In the ocean, the fry remain in coastal areas for several months before they move offshore (Urawa, 2000; Yatsu and Kaeriyama, 2005). The catch of chum salmon in Japanese fisheries consists mainly of fish produced in Japan. New information indicates that Japanese-produced chum salmon spend their first marine year in the southern Okhotsk Sea. In the fall, the juveniles move into the northern North Pacific and the Bering Sea where most remain for 3 to 5 years. Maturing chum salmon begin their return migration about April–May and arrive at the rivers where they were released about August–September. All chum salmon die after spawning, although natural spawning rarely occurs in Japan. Chum salmon are basically zooplankton feeders.

Table 15 Walleye pollock catches (t).

Year	Catch (FAO)	Pacific stock	North Japan Sea stock
1980	1,552,429		–
1981	1,595,302	294,765	–
1982	1,570,373	246,506	–
1983	1,434,430	279,916	–
1984	1,604,929	283,354	–
1985	1,533,179	274,466	117,468
1986	1,421,802	206,541	79,942
1987	1,312,510	236,513	83,510
1988	1,259,095	221,344	120,644
1989	1,153,750	196,721	130,583
1990	871,408	166,001	128,417
1991	540,946	166,901	128,391
1992	498,756	159,028	127,012
1993	382,308	145,315	75,531
1994	379,351	141,724	64,777
1995	338,507	146,632	65,005
1996	331,163	112,661	80,746
1997	338,785	164,989	70,846
1998	315,987	190,360	56,320
1999	382,385	245,151	51,617
2000	300,001	209,900	41,847
2001	241,881	129,982	45,615
2002	213,254	110,377	60,074

Source of catch by stock: FAJ (2004a)

Fishery

Since the 1970s, the high seas salmon fishery has declined and in recent years has been confined to the Russian EEZ (Table 16). Thus, the recent chum salmon catch is mainly from the coastal set net fishery around Hokkaido and northern Honshu. There is a relationship between size and age at maturity and abundance of chum salmon (Kaeriyama, 1989).

Climate and ocean effects

There are natural fluctuations in Pacific salmon abundance that are related to fluctuations in large-scale climate indices and to regime shifts (Beamish and Bouillon, 1993; Yatsu and Kaeriyama, 2005). It is generally accepted now that the early assumptions that climate and ocean impacts on survival followed a random model are not correct. However, the mechanisms that result in trends in production are poorly understood. It is known that coastal environments are important. For example, Saito (2002) detected positive correlations between marine survival rates and coastal SST in particular areas of Hokkaido and northern Honshu. There is not a good relationship between PDO and catch for chum salmon produced in Japan (Kaeriyama, 2004; Yatsu and Kaeriyama, 2005). Thus, marine survival of Japanese chum salmon is correlated more with the coastal environment than with the PDO or Aleutian Low Pressure Index.

Table 16 Chum salmon catches (t).

Year	Catch (FAO)	Catch (NPAFC*)
1980	87,713	96,800
1981	112,361	120,800
1982	102,654	111,80
1983	125,196	133,50
1984	127,712	136,30
1985	167,960	176,70
1986	142,081	157,52
1987	136,641	146,60
1988	149,369	159,20
1989	169,245	181,03
1990	207,989	222,88
1991	191,596	197,58
1992	149,540	137,20
1993	195,892	187,86
1994	205,647	191,52
1995	249,982	231,05
1996	280,855	266,15
1997	250,837	237,35
1998	190,553	178,54
1999	171,182	158,30
2000	151,123	139,93

* North Pacific Anadromous Fish Commission

Pacific saury (*Cololabis saira*)

Biology

Pacific saury have a life span of 2 years or less. The age of the first maturation is at about 6 months. Their maximum size is 34 cm in body length. Pacific saury are zooplankton feeders.

Fishery

Two stocks occur around Japan. The Northwestern Pacific stock occurs in the northwestern Pacific from the Pacific coast off Japan to 170°E (Odate, 1977). The Japan Sea stock occurs in the Japan Sea. Most catches of Pacific saury in Japan are made from the Northwestern Pacific stock (Table 17). Catches from the Japan Sea stock are much smaller than those from the Pacific Ocean. The distribution is very broad and includes the EEZ waters of Russia, Korea, and Japan. Gong *et al.* (1983) reported that Pacific saury remain in the southern region of the Japan Sea and the East China Sea in winter. The Northwestern Pacific stock spawns mainly in winter throughout the subtropical waters, including the Kuroshio and Kuroshio Extension, much wider areas than previously assumed. They also spawn in spring and autumn in the KOTZ. Baytaluk and Davydova (2001) reported that large numbers of larvae were found in the central Pacific Ocean in spring. In this report we consider that the two stocks are geographically divided, consistent with Odate (1977) who suggested that the Central Pacific stock occurs in the central part of the North Pacific Ocean separately from the Northwestern Pacific stock. However, Nagasawa *et al.* (1988) stated that separation of the Northwestern Pacific stock and the Central Pacific stock is doubtful, based on the parasite studies. Accordingly, it is possible that there is only one stock ranging from the northwestern Pacific to the central part of the North Pacific.

Pacific saury are fished using stick-held dip-nets. Drift gill net fisheries and set net fisheries are used locally or seasonally, but account for less than 5% of the catch. The fishery for the Northwestern Pacific stock averaged 280,000 t from 1980 to 2000 (Table 15). There is no apparent trend in catches.

Climate and ocean effects

The optimum SST range for hatching is from 14° to 20°C. The lower limit of the distribution in the feeding grounds is about 4°C. The optimum SST range in the feeding grounds located in the subarctic waters, including the Oyashio, is from 8° to 12°C.

Ebisawa and Snow (1999) reported that SST of the Kuroshio (southeast of Honshu) in winter is positively correlated with the catch per unit effort (CPUE) of the Pacific saury stick-held dip-net fishery. The CPUE of large-sized saury in this fishery is related to SST in the winter of the previous 2 years. Kurita (2001) reported that the abundance of zooplankton in the feeding areas (the Oyashio waters) affected the condition of Pacific saury, which may influence the success of the spawning. However, an actual relationship between zooplankton abundance and the success of spawning has not been reported. Tian *et al.* (2002) stated that the occurrence of El Niño and MOI (Monsoon Index) positively affected the abundance of Pacific saury (especially for large-sized fish). Productivity is significantly related to the Southern Oscillation Index (SOI), but does not appear to be related to the PDO (Figs. 23 and 24) and thus, to regime shifts. The clear relationship to SST in the Kuroshio and Kuroshio Extension in winter and in their spawning area indicates that climate-related changes in the ocean will affect the production of Pacific saury.

Table 17 Pacific saury catches (t) by country.

	Catch (FAO)	Japan	Russia	Korea	Taiwan	Northwestern Pacific stock total
1980	187,155	192,449	38,579	–	–	231,028
1981	160,319	159,304	31,716	–	–	191,020
1982	206,958	192,883	23,439	–	–	216,322
1983	239,658	232,560	7,800	–	–	240,360
1984	209,974	223,769	0	–	–	223,769
1985	245,944	259,247	7,500	–	–	266,747
1986	217,229	225,718	11,700	–	–	237,418
1987	197,084	210,249	23,400	–	–	233,649
1988	291,575	287,927	50,300	1,960	9,992	350,176
1989	246,821	246,713	68,500	3,236	17,531	335,980
1990	308,271	310,592	61,850	17,612	8,570	398,624
1991	303,567	298,935	46,461	25,135	10,780	381,311
1992	265,884	258,717	44,016	33,708	23,030	359,471
1993	277,461	273,702	48,022	40,154	11,460	373,338
1994	261,587	250,704	23,846	32,280	12,550	319,380
1995	273,510	272,901	24,115	30,996	13,772	341,784
1996	229,227	231,238	9,726	18,729	8,287	267,980
1997	290,812	285,438	6,525	50,227	21,887	364,077
1998	144,983	140,110	5,097	13,926	23,000	182,133
1999	141,011	134,937	5,050	18,036	–	158,023
2000	216,471	211,883	16,345	–	–	228,228
2001	–	266,344	–	–	–	266,344

Source of catch by stock: FAJ (2004a)

Common squid (*Todarodes pacificus*)

Biology

Common squid is a coastal/offshore species with a life span of approximately 1 year and a maximum mantle length of 27 cm (Murata, 1990). Although this species is abundant in the entire area of the Japan Sea, it is confined to coastal and offshore waters in the Pacific Ocean. They change their prey from zooplankton to small fishes and squids as they grow.

Fishery

Off Japan, an autumn cohort and a winter cohort are recognized for management purposes. The autumn cohort consists of squid hatched from October to December in the East China Sea and the southern Japan Sea (Murata, 1990). The autumn cohort migrates to its feeding area around the northern Japan Sea and returns to its spawning grounds via the Japan Sea. Extensive tagging studies have identified the migration pattern, and para-larval distribution indicates that the spawning area is in the East China Sea and southern Japan Sea. The winter cohort is composed of squid that hatch during December to February in the East China Sea. Tagging studies have shown that these young squid migrate to their feeding grounds around Hokkaido mainly via the northwestern Pacific (Murata, 1990). Most of the winter cohorts return to their spawning grounds through the Japan Sea. In general, the two cohorts have distinct hatching periods, season-specific body sizes, and migration patterns. However, the separation is not perfect because of overlapping length distributions. Thus, the portioning of catches using mean mantle length in the summer is not exact (Kidokoro, 2002). In addition to Japan, the stocks are fished by Korea and China using jigs, trawls, purse seines, and set nets. Proportions of catch by Japan and Korea in recent years are more than 90% (Table 18). CPUE of commercial and research jig fishing can be used as a proxy of stock abundance. The biomass of common squid was high in the 1960s, declined in the 1970s, and remained at low levels through to the early 1990s when it increased substantially (Fig. 21).

Climate and ocean effects

In general, warmer temperature conditions around Japanese waters are favorable for common squid (Sakurai *et al.*, 2000). The area that is suitable for spawning for both stocks is considered to be a major factor affecting abundance (Sakurai *et al.*, 2000). Hatchlings are abundant in SSTs of 17° to 23°C. This temperature range, and ocean conditions favorable for pre-spawning behaviour and post-spawning retention of eggs within a mid-water layer, are important for year-class survival (Sakurai *et al.*, 2000).

The biomass of common squid increased in the mid-1980s (Fig. 21). Productivity is positively correlated with winter SST along the Kuroshio path and its southern areas. Abundance is negatively correlated to the PDO without a lag (Fig. 25). Common squid and jack mackerel productivity and biomass trends are similar and roughly opposite to Japanese sardine (Figs. 26 and 27).

Neon flying squid (*Ommastrephes bartrami*)

Biology

Neon flying squid is an oceanic species that has a life span of slightly longer than 1 year and that grows to a size of 60 cm mantle length in females and 45 cm in males (Yatsu *et al.*, 1998). They are voracious predators of small fishes and squids.

Fishery

Two cohorts are recognized. The winter–spring cohort and the autumn cohort have distinct hatching periods, body sizes, and migration patterns (Yatsu *et al.*, 1998). The winter–spring cohort has been the target of the traditional jig fishery in the northwestern Pacific, west of 160°E. The autumn cohort is distributed mainly in the central and eastern North Pacific. This cohort was the target of the international driftnet fishery beginning in 1978 and ending in 1992 by international agreement. A new jig fishery on this cohort started in the mid-1990s throughout the western and central North Pacific.

Table 18 Common squid catches (t).

Year	Catch[1]	Japan and Korea total	Autumn cohort, Japan	Autumn cohort, Korea	Winter cohort, Japan	Winter cohort, Korea
1980	405,420	379,258	176,853	37,469	153,914	11,022
1981	290,381	248,029	134,366	29,962	66,948	16,753
1982	274,206	236,662	130,867	38,360	51,870	15,565
1983	245,855	229,264	135,327	25,908	56,650	11,379
1984	286,501	218,129	116,720	25,017	61,799	14,593
1985	214,275	174,285	103,719	30,548	27,687	12,331
1986	141,457	130,573	55,430	23,265	37,928	13,950
1987	262,025	249,485	144,017	43,580	44,538	17,350
1988	227,786	200,172	108,976	31,915	41,670	17,611
1989	319,790	277,205	146,221	41,767	65,098	24,119
1990	321,459	285,474	134,794	45,462	75,386	29,832
1991	402,976	355,623	130,359	66,914	115,361	42,989
1992	545,209	531,002	154,830	72,712	236,380	67,080
1993	548,365	530,156	148,048	131,471	165,940	84,697
1994	504,425	483,917	128,121	128,597	166,224	60,975
1995	513,413	497,352	128,135	125,558	168320	75,339
1996	715,908	696,630	176,916	139,259	267,095	113,360
1997	603,367	590,574	139,821	138,714	225,793	86,246
1998	378,605	344,504	108,089	102,990	73,401	60,024
1999	497,887	478,196	140,482	160,140	98,917	78,657
2000	570,427	564,960	104,157	152,677	234,493	73,633

[1] All nations' catch for "Japanese flying squid" from FAO statistics; source of catch by stock: FAJ (2004a)

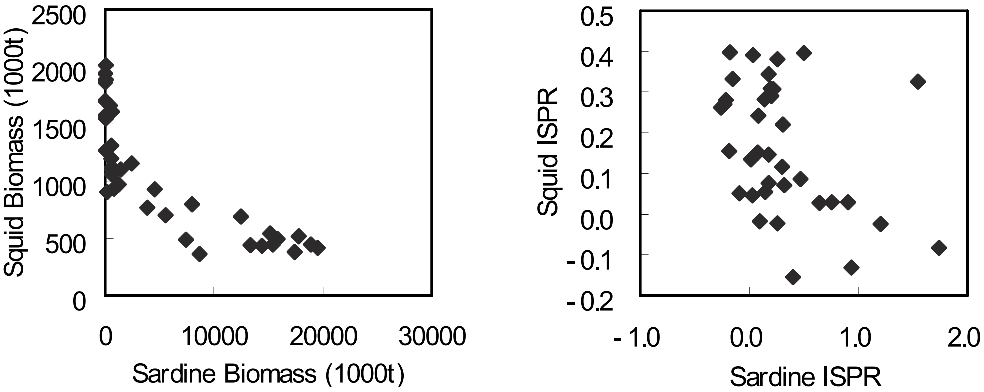


Fig. 27 Relationships between sardine and common squid biomass and productivity (adopted from Yatsu *et al.*, 2005).

Tagging surveys were not successful in providing information about the stock structure. However, a study of helminth parasites identified a central North Pacific and an eastern North Pacific stock within the autumn cohort (Nagasawa *et al.*, 1998). The autumn cohort is now fished by Japan, China, and probably Korea and Taiwan. Recent catch data by all countries may be incomplete. CPUE from research driftnet studies in the early summer can be used as a proxy of the abundance of the Central North Pacific stock within the autumn cohort (Yatsu *et al.*, 2000).

Prior to the moratorium on driftnet fishing in 1992, catches by all countries increased steadily from the early 1970s to 300,000–350,000 t in the early 1980s. Since 1993, Japanese annual catches have ranged between 15,000 and 85,000 t (Table 19).

Climate and ocean effects

The SST at the spawning grounds ranges from 22° to 26°C, as indicated by para-larval distribution (Yatsu *et al.*, 2000). SST at the feeding grounds ranges from 10° to 25°C, with the densest concentrations of squid occurring at temperatures between 15° and 22°C (Yatsu *et al.*, 1993). SST should be an important factor affecting the spawning, survival, and growth of para-larvae, hence stock abundance (Yatsu *et al.*, 2000). Zooplankton mean density in the Central North Pacific (Sugimoto and Tadokoro, 1998) is significantly negatively correlated to the research driftnet CPUE ($r = -0.57$, $P < 0.05$, $df = 14$). SSTs in the hatching and nursery areas (30°–36°N, 170°–150°W from October to March) and during pre-recruitment (30°–36°N, 170°–150°W from January to June) had some positive relationship to abundance after the moratorium on driftnet fishing in 1992 (Yatsu *et al.*, 2000).

Possible Greenhouse Gas-induced Changes in the Climate and Ocean Environment

It is now recognized that natural changes in climate have major impacts on the abundance of marine fish. However, while there is a great amount of evidence that climate affects fish, the mechanisms that cause the fluctuations in abundances are not well understood. We know that major climate events associated with ENSO (El Niño–Southern Oscillation) regimes, regime shifts, and 50- to 70-year climate trends are reflected in the population dynamics of most fishes. Unfortunately, we are not yet able to forecast accurately how global warming will have an impact on these natural climate fluctuations. Potential impacts will change the strength and direction of ocean currents which will affect the larvae transportation and availability of nutrients which, in turn, will affect the food of fishes.

In particular, the food for larval and juvenile fish in their first ocean year appears to be critical for their survival over the first marine winter and for their recruitment into commercial fisheries because survival rates are extremely low during larval and juvenile stages. Ocean temperatures will change and, in most ecosystems, will warm. Warmer temperatures affect metabolic functions of fish as well as their behaviour, food, and predators. Although we cannot predict accurately how the ocean ecosystems will change, we are improving our understanding and are able to make informed

Table 19 Japanese neon flying squid catches (t) by country and fishery.

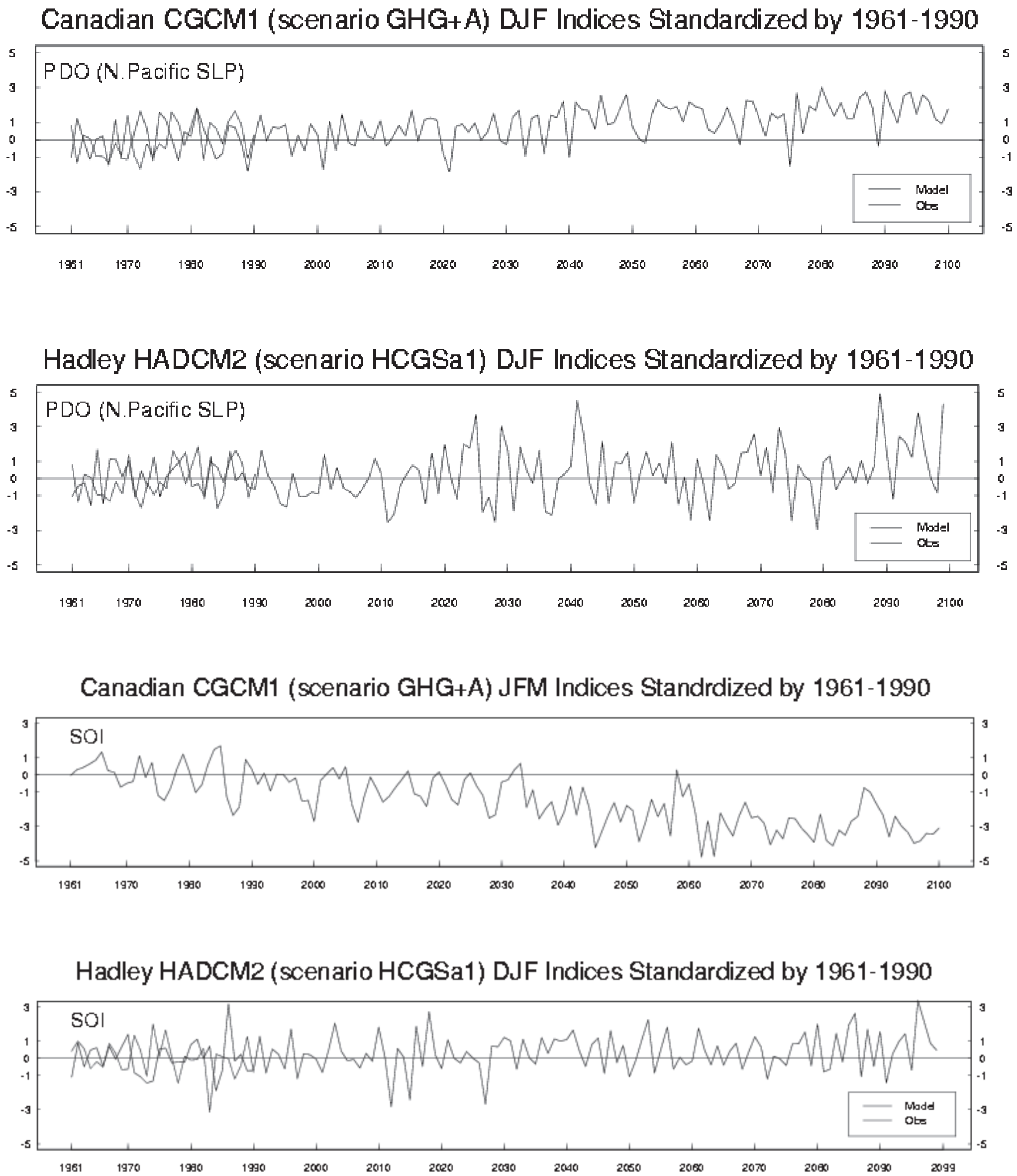
Year	Total catch	Jig catch, Japan	Driftnet catch, Japan	Driftnet catch, Korea	Jig and driftnet, Taiwan	Jig catch, China
1980	198,000	70,000	122,000	0	6,000	0
1981	175,000	57,000	103,000	0	15,000	0
1982	242,000	58,000	159,000	0	25,000	0
1983	322,000	45,000	216,000	38,000	23,000	0
1984	230,000	29,000	124,000	49,000	28,000	0
1985	342,000	51,000	198,000	71,000	22,000	0
1986	248,000	23,000	152,000	59,000	14,000	0
1987	332,000	21,000	208,000	84,000	19,000	0
1988	285,000	16,000	158,000	101,000	10,000	0
1989	351,000	16,000	171,000	134,000	30,000	0
1990	360,000	34,000	188,000	124,000	14,000	0
1991	196,000	13,000	102,000	69,000	12,000	0
1992	177,000	2,000	100,000	61,000	10,000	4,000
1993	–	15,000	0	–	–	13,000
1994	–	71,000	0	–	–	17,000
1995	–	60,000	0	–	–	69,000
1996	–	58,000	0	–	–	74,000
1997	–	63,000	0	–	–	60,000
1998	–	85,000	0	–	–	–
1999	–	26,000	0	–	–	–
2000	–	28,000	0	–	–	–

Source of catch by stock: FAJ (2004b)

speculation. If we recognize that changes will occur and that our understanding of the impacts is imperfect, it becomes evident that our management of the fisheries is critical. Overfishing at the beginning of a prolonged trend of poor ocean productivity could reduce a stock to such levels that literally could take centuries to recover.

Changes in the climate and ocean environment over and around Japan as a result of global warming can only be approximated (Nishioka and Harasawa, 1998). At the time of a doubling of CO_2 (relative to 1990 levels) it is estimated that air temperature would increase between 1.0° and 2.5°C. Sea level rises on the coast of the Japan Sea would be 10 to 20 cm higher and about 15 cm higher along the Pacific Ocean and Okhotsk Sea coasts. Along the coast of the Japan Sea, the SST increase would be 1.6°C, 1.2° to 1.6°C along the Pacific coast, and 1.8°C along the coast of the Okhotsk Sea. The strength of the Kuroshio Current depends on the changes in the subtropical Pacific gyres. If the temperature difference between higher and lower latitudes is reduced, trade winds and westerly winds are estimated to weaken. As a consequence, the strength of the Oyashio and Kuroshio would weaken, and the mixed layer depth would become shallower, reducing plankton production. There seems little doubt that global warming will change the path of the Kuroshio and the structure of the Oyashio and the Transition area. However, there is another interpretation in which global warming impacts on the gyres in the subarctic Pacific could result in more periods of stormy winters similar to the conditions from 1977 to 1989 (Mote *et al.*, 1999).

According to Mote *et al.* (1999), over the next 100 years there will be a trend of increasingly positive PDO or stormy periods according to two major GCM models, the UK Hadley Centre model and the Canadian Climate Centre model (Fig. 28; Beamish and Noakes, 2002). Also, the above two models predict an increase in the Arctic Oscillation (AO) in the next century (Fig. 29), though the two scenarios forecast SOI differently. Assessment of greenhouse gas effects on fisheries is difficult because of the unexpected ecosystem dynamics, even though some species in the Japanese fisheries have simpler life histories than species such as Pacific salmon (Mote *et al.*, 1999; Beamish and Noakes, 2002). Climate effects will result in different impacts, depending on ecosystem structure – species types of prey, predators, competitors, and changes in their associations. It is important to preserve the natural buffering characteristics of individual stocks (Shuter *et al.*, 2002). For example, diverse age structure, genetic diversity, migration pathways, and multiple habitats are essential for mitigating unexpected climate changes. Although small pelagics around Japan are genetically uniform (Okazaki *et al.*, 1996), their natural buffering capacity will not be easily lost because of their adaptability (Kuroda, 1991; McFarlane *et al.*, 2002).


Canadian CGCM1 (scenario GHG+A) DJF Indices Standardized by 1961-1990

Hadley HADCM2 (scenario HCGSa1) DJF Indices Standardized by 1961-1990

Canadian CGCM1 (scenario GHG+A) JFM Indices Standrdized by 1961-1990

Hadley HADCM2 (scenario HCGSa1) DJF Indices Standardized by 1961-1990

Fig. 28 Observed and predicted PDO (Pacific Decadal Oscillation) and SOI (Southern Oscillation Index) under the two major models (Canadian Climate Centre CGCM1 and Hadley HADCM2) from 1961 to 2100 (adopted from http://www.usgcrp.gov/usgcrp/nacc/background/scenarios/indices.html, with permission).

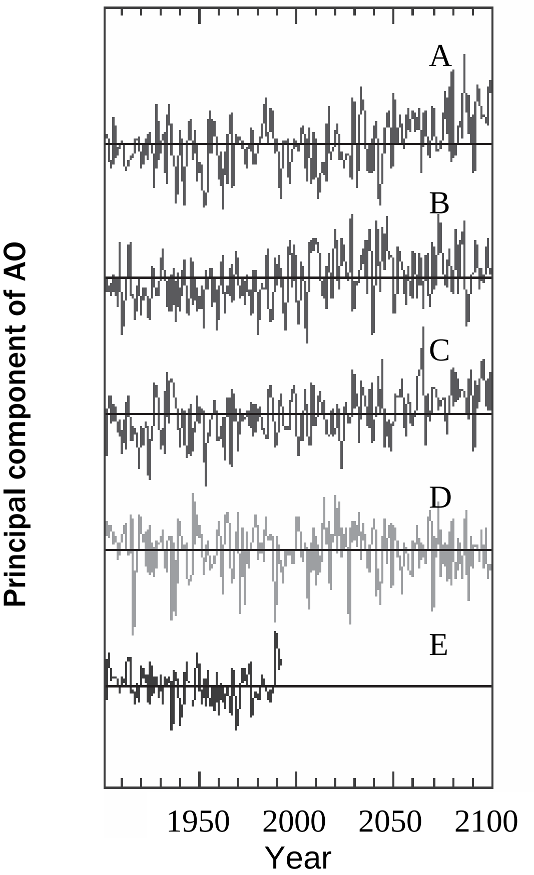


Fig. 29 Simulated and actual Arctic Oscillation (AO) time series (November–April averages). A–C: three independent climate change simulations; D: control simulation; E: observed (adopted from Fyfe *et al.*, 1999; http://www.usgcrp.gov/usgcrp/nacc/background/scenarios/indices.html, with permission).

Ono *et al.* (2002) detected a decreasing trend in primary production in the Oyashio during the 1970–1993 period. If this trend continues, production of small pelagics and other predatory species will decrease in both the Kuroshio and Oyashio areas. This is because most of the small pelagic fishes around the Pacific coast of Japan utilize the productive Oyashio area as feeding grounds during spring–autumn. Shifts in the geographic range of sardine populations corresponding to temperature changes will not result in a collapse of stocks because their behaviour is flexible (*e.g.*, the spawning ground for sardine shifted considerably around Japan; Kuroda, 1991), and they have sustained themselves during changing temperatures over evolutionary time.

Some of the observed shifts in biological productivity of sardine, chub mackerel and common squid correspond to regime shifts in SST (1957/58, 1970/71, 1976/77, 1988/89; Yasunaka and Hanawa, 2002), and in PDO (Figs. 23–26). Biological productivity of Pacific saury, jack mackerel and walleye pollock were not evidently related to regime shifts; however, decadal and inter-annual fluctuations were observed. For Pacific saury, this is probably because of the correlation of productivity with ENSO (Fig. 25; Tian *et al.*, 2002). Since biomass and productivity of sardine and common squid are negatively correlated (Fig. 27), there might be an inter-species competition in addition to unknown linkages to PDO variability. It should also be remembered that an increase in biomass is a result of accumulation of enhanced productivity over time and that biological productivity may be decreased by increased biomass known as the density-dependent effect.

The 1970/71 regime shift resulted in extremely high production rates for sardine and chub mackerel. The well known 1976/77 regime shift was detected in the productivity and recruitment of chub mackerel, and possibly Pacific saury, but did not seem to affect sardine. Yatsu and Kidokoro (2001) found coherent shifts in body size and intrinsic population growth rate of common squid in 1976/77 and around 1986. The 1989 regime shift, when the AO shifted to a positive phase, affected sardine and chub mackerel productivity and recruitment, production–biomass relations (Yatsu *et al.*, 2003), and possibly jack mackerel recruitment.

In general, peaks in biomass lag up to a decade from the SST regime shifts, probably because of the time required for biomass accumulation in response to shifts in the stock-specific production rates and fishing mortality. Recruitment corresponds more closely with the SST regime shifts than with productivity, indicating early survival is the most sensitive stage in species life history to oceanographic changes. Yatsu *et al.* (2003) argued that productivity is less sensitive to environmental variability than to recruitment, as production is the composite of recruitment, individual growth and natural mortality over a broad range of ages. Even if these relationships between the PDO and AO were determined accurately, prediction of sardine and chub mackerel populations is difficult because the positive PDO and AO have a contradicting relationship to sardine and chub mackerel productivity. Jack mackerel will increase, as its production is negatively related to the Oyashio southern limit, which has a negative relationship with the PDO (Fig. 25), and geographic distribution is confined to central and southern Japan, *i.e.*, jack mackerel seem independent of Oyashio productivity. Under the decreasing scenario of Oyashio productivity, the Pacific saury production rate will decrease.

Possible Impacts of Climate Change on Fish Populations and Fisheries

A summary of linkages between stock trends and environmental conditions for different species is provided in Table 20.

Chub mackerel

There is clear evidence that climate, and climate shifts, affect the production of chub mackerel. There also is evidence that overfishing of immature fish affects the ability of the population to respond to periods of favourable environmental conditions. It is apparent that future changes in climate will have an impact on production. Warming of the spawning areas in the winter will have a negative impact, as will more intense and frequent periods of extreme winter storminess (more intense Aleutian Lows and a positive PDO).

Jack mackerel

Jack mackerel may increase in abundance as their productivity is negatively related to the southern limit of the Oyashio, which has a negative relationship with the PDO.

Japanese sardine

In the Tsushima Current stock, reproductive success is negatively affected by winter temperature in the southwestern Japan Sea (Hiyama *et al.*, 1995). A similar effect of winter temperature is also known in the Pacific stock (Ebisawa and Kinoshita, 1998; Noto and Yasuda, 1999). The impacts of global warming induced climate change on Japanese sardine will relate to impacts on the dynamics of the western gyres, including the Kuroshio, Kuroshio Extension and Oyashio, and the structure of the Transition area. If the impact results in more intense and more extreme winter Aleutian Lows, and thus periods of positive PDO, then sardine abundance would continue to fluctuate, perhaps with all-time record highs of abundance. However, other models suggest that winds will be reduced, and this could result in periods of increased stability, reduced plankton productivity, and low sardine survival, typical of the period from the late 1940s to the mid-1970s.

Anchovy

The production of anchovy is opposite to that of Japanese sardine and this relationship is expected to continue. Therefore, a key to understanding the impacts of climate change on anchovy is to look at the behaviour of sardine. There is not a good relationship between PDO and other major ocean–climate indices and production, but there are persistent trends in production that change quickly to opposite trends, indicating that climate and ocean conditions are important. A key to the understanding of the impacts is the response of major atmospheric circulation patterns in the winter to increased greenhouse gas production. If winds are reduced, anchovy production may be generally increased as sardine production is reduced. The opposite would occur if there are more frequent periods of intense Aleutian Lows.

Walleye pollock

There is no relationship between walleye pollock productivity or catch and the PDO, but there ae decadal-scale fluctuations. This indicates that climate effects are important and that there is a persistence in climate-related impacts on walleye pollock. They are at the southern limit of their range around Japan and a warming of the ocean would reduce their productivity. Because walleye pollock are also relatively long-lived (maximum ages of about 30 years), there is a resiliency in the population to prolonged unfavourable ocean conditions if the stocks are not overfished. This resiliency could ensure that the stocks are maintained, and even enhanced, during the periods when naturally cold ocean conditions occur.

Chum salmon

Chum salmon are virtually all produced in hatcheries and the number of fry produced has been maintained at about 2 billion in recent years. This means that egg-to-fry survival is independent of climate impacts, either directly in fresh water or indirectly in the regulation of the number of eggs produced (as would occur in naturally spawning stocks).

However, there will be an impact on chum salmon in the ocean during the early marine rearing period. In general, Pacific salmon at their southern range in the ocean are expected to have reduced marine survival and thus, reduced production as a consequence of the warming of the sea surface and the reduction in plankton preferred by juveniles. A reduction in food reduces carrying capacity and reduces production either by increased predation mortality or by reduced growth in the early marine period, and a subsequent reduced ability to survive harsh environmental conditions in the first marine winter.

Table 20 Summary of linkages between stock trend and environmental conditions in major stocks.

	Biomass trend	**Production/ recruitment trend**	**Environmental links (excluding SST)**	**SST link**	**Regime effect**
Chub mackerel	Similar biomass trend to sardine up to 1988, then there is overfishing	Recruitment is similar to saury	- Positive PDO and negative AO increase abundance, - Positive AO increases recruitment, - More Kuroshio transport reduces biomass	Warm winter SST in Kuroshio reduces recruitment	There is a regime effect
Jack mackerel	Similar biomass trends to common squid		More production with more southern Oyashio	Warm spring SST in East China Sea is related to biomass but reduces recruitment	There seems to be no regime effect but biomass trajectory is similar to that of common squid
Japanese sardine	Opposite response to common squid and jack mackerel	Production opposite to common squid	- Positive PDO and negative AO increase abundance, - More southern Oyashio increases abundance, - More Kuroshio transport reduces production	High winter SST in Kuroshio Extension reduces recruitment	There is a regime effect
Walleye pollock	Decadal fluctuations are evident	There are sporadic occurrences of strong year classes			There is no regime effect but decadal-scale fluctuations occur
Pacific saury		Recruitment similar to chub mackerel	- Positive SOI increases productivity, - Positive AO decreases productivity with lag of 1 year	Warm winter SST in Kuroshio reduces recruitment	There is no regime effect but there is a relationship with SOI and inter-annual fluctuations
Common squid	- Similar biomass trends to jack mackerel, - Opposite response to sardine	Production opposite to sardine	Positive PDO reduces biomass, as in 1977–1990		There is a regime effect

SST = sea surface temperature, PDO = Pacific Decadal Oscillation, AO = Arctic Oscillation, SOI = Southern Oscillation Index

Pacific saury

The abundance trend of Pacific saury is related more to ENSO than to the PDO, suggesting that it is necessary to understand how global warming will change the pattern of ENSO to understand the impacts on Pacific saury. Warm surface waters in the Kuroshio and subtropical waters south of Shikoku and Kyushu are associated with reduced recruitment. Thus Pacific saury may be less abundant under a global warming scenario.

Common squid

Common squid should respond to greenhouse gas-induced climate change in a manner similar to jack mackerel, and opposite to Japanese sardine. If jack mackerel abundance increases because its productivity is negatively related to the Oyashio southern limit, which is negatively related to PDO, then common squid should also increase in a decadal fashion. Common squid were reduced in abundance during the 1980s when the PDO was positive and the Aleutian Low was strong. If there are more frequent periods of intense Aleutian Lows, there may be more frequent periods of reduced abundance of common squid. Because common squid live only for 1 year, their abundance trends change quickly.

Neon flying squid

There is no apparent relationship to the PDO. There is a relationship between SST and abundance which indicates that warmer surface waters may be more productive for neon flying squid.

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The Fishery

China has the largest fishery in the world. The total production was 5.1 million t in 2005, of which 28.5% was from marine captures. Catches from marine capture fisheries reported by the UN Food and Agriculture Organization (FAO) increased from 3.1 million t in 1980 to a maximum of 17.2 million t in 1998 and 1999 (Table 21, Fig. 30A and B). Catches in 2002 declined about 4% from the 1999 levels. China's marine capture fisheries have accounted for about 18% of the world catch in recent years (Table 21, Fig. 31) of which marine fish make up the largest group in the catch (Fig. 32). Much of the catch is reported in species aggregates, such as marine fishes (nei), or scads (nei). Scads include, for example, *Trachurus japonicus*, *Decapterus maruadsi*, *Septipinna taty*, and *Sardinella zunasi*. Some of the key species in the Yellow Sea are listed in Table 22 and represent about 17 to 20% of the catch over the past few decades.

Aquaculture is the major supplier of seafood in China. Production of seafood from aquaculture just exceeded wild production in 1985 and by 2003 was 1.4 times larger than the wild catch. Marine aquaculture consists mostly of shrimp, molluscs, and aquatic plants, with fish representing about 2.5% of the approximately 20.9 million t of marine aquaculture production in 2003. A common food for cultured fish is the bycatch in marine fisheries. In 2003, marine fish production was 519,000 t, and was expected to increase substantially. China is also one of the world's major importers of fish meal and, increasingly, more seafood for domestic consumption.

Major Coastal Fishing Areas

The major coastal fishing areas are in the Bohai Sea, the Yellow Sea, and the East China Sea (Fig. 33). The Yellow/Bohai Sea is bordered by China, Democratic People's Republic of Korea and Republic of Korea, and is located at latitudes of 32°–41°N, and longitudes of 118°–126°30′E. A border line, separating the Yellow Sea from the East China Sea, is commonly drawn from the mouth of the Yangtze River to Jeju Do. The Yellow Sea large marine ecosystem, as internationally defined, also includes the Bohai Sea. Major rivers discharging directly into the Yellow/Bohai Sea include the Han, Datung, Yalu, Huanghe and Sheyang, from the middle region to the north, and the Yangtze River in the south. The Yellow Sea annually receives more than 1.6 billion t of sediments from the rivers (Valencia, 1988). It covers an area of about 460,000 km^2 and has a geologically unique bottom. The seafloor has an average depth of about 40 m, a maximum depth of 140 m north of Jeju Do, and slopes gently from the Chinese continent, and more rapidly from the Korean Peninsula to a north–south trend of bathymetric contour. There is a depression with smooth terrain in the central part of the Yellow Sea which is an important overwintering ground for many fish species. The Bohai Sea and the shallow waters along the coast in the Yellow Sea are important spawning grounds for most species distributed in the Yellow Sea. The Bohai, Yellow and East China seas are marginal seas of the Pacific Ocean bounded by the Korean Peninsula and China. The Yellow Sea is a semi-enclosed shelf sea with distinct bathymetry, hydrography, productivity, and trophically dependent populations. Shallow, but rich in nutrients and resources, the sea is most favourable for coastal and offshore fisheries, and has had well-developed multi-species and multi-national fisheries. However, over the past several decades, many changes in productivity, biomass yields, species composition and shift in dominance have occurred. Overexploitation is the principal reason for the changing state of the ecosystem, but natural environmental perturbation should be considered an important driving force causing changes in the species composition and biomass yields, at least for pelagic species and shellfish.

The Yellow Sea is one of the most intensively fished areas in the world. China has increased the total annual catch from about 0.5 million t in the 1950s and 1960s to around 1.5 million t in recent years. Four provinces and one municipality, including Lioaning, Hebei, Shandong, Jiangsu, and Tianjin are along the Chinese coast in the Yellow Sea.

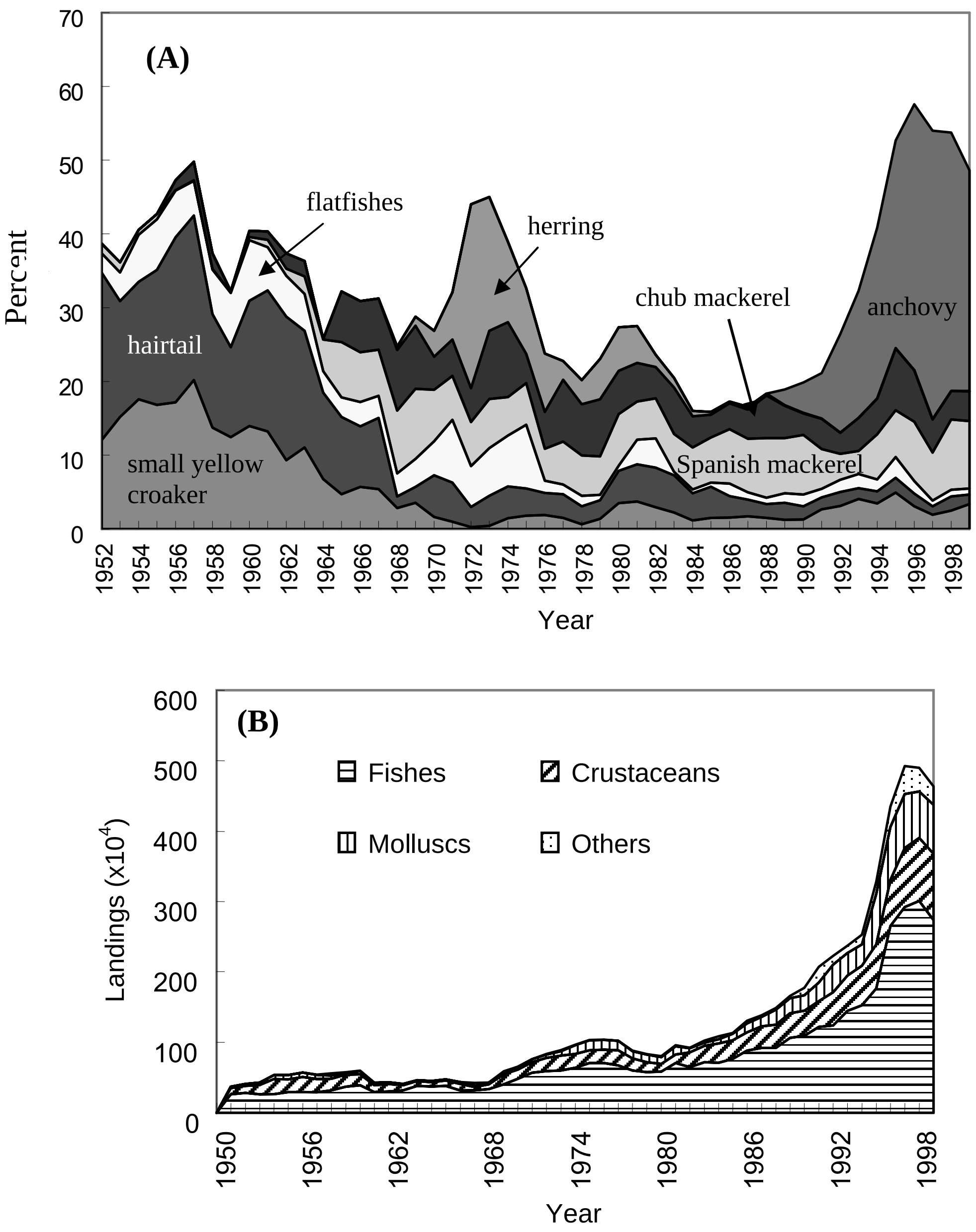

Fig. 30 (A) Proportion of major species in total fish landings from northern China; (B) total landings from northern China. Some of the catches were from the East China Sea.

Table 21 Catch (in millions of t) for the world, China, and the world, excluding China, from 1950 to 2002 (FAO, 2003).

Year	World catch	China catch	World catch – China catch
1950	18.697	0.880	17.817
1951	21.147	1.249	19.897
1952	22.947	1.558	21.389
1953	23.399	1.723	21.676
1954	25.348	2.032	23.316
1955	26.737	2.206	24.531
1956	28.405	2.369	26.036
1957	28.542	2.042	26.500
1958	29.137	2.091	27.046
1959	31.517	2.134	29.383
1960	33.852	2.215	31.637
1961	37.645	2.396	35.249
1962	40.974	2.539	38.435
1963	42.026	2.491	39.535
1964	46.621	2.466	44.154
1965	47.603	2.530	45.073
1966	51.467	2.504	48.963
1967	54.798	2.509	52.289
1968	58.092	2.626	55.467
1969	56.570	2.553	54.017
1970	62.767	2.490	60.277
1971	62.857	2.704	60.153
1972	58.541	3.009	55.533
1973	59.000	3.099	55.901
1974	62.292	3.385	58.908
1975	61.810	3.497	58.313
1976	65.214	3.597	61.616
1977	63.778	3.623	60.155
1978	65.934	3.416	62.519
1979	66.421	3.042	63.378
1980	67.185	3.139	64.045
1981	69.408	3.135	66.272
1982	71.114	3.490	67.624
1983	71.060	3.645	67.415
1984	76.671	3.918	72.754
1985	78.236	4.178	75.057
1986	83.725	4.759	78.965
1987	84.321	5.378	78.942
1988	87.796	5.749	82.047
1989	88.312	6.165	82.147
1990	84.778	6.654	78.123
1991	83.723	7.372	76.351
1992	85.198	8.323	76.875
1993	86.562	9.351	77.210
1994	92.094	10.867	81.227
1995	92.396	12.563	79.834
1996	93.862	14.182	79.679
1997	94.314	15.722	78.592
1998	87.687	17.230	70.457
1999	93.790	17.240	76.550
2000	95.516	16.987	78.528
2001	92.785	16.529	76.346
2002	93.212	16.553	76.659

The Yellow Sea contains an abundance of living marine resources. There are about 300 fish species, 41 crustaceans, and 20 cephalopods, but only around 50 species are represented in the fishery. Warm-water species dominate, accounting for 46.7%, with temperate water species making up 44.7%. Only a few cold water water species are found in the area. Tang *et al.* (2003) provide a detailed account of the changes in the major fisheries resources in the Bohai Sea (Table 22).

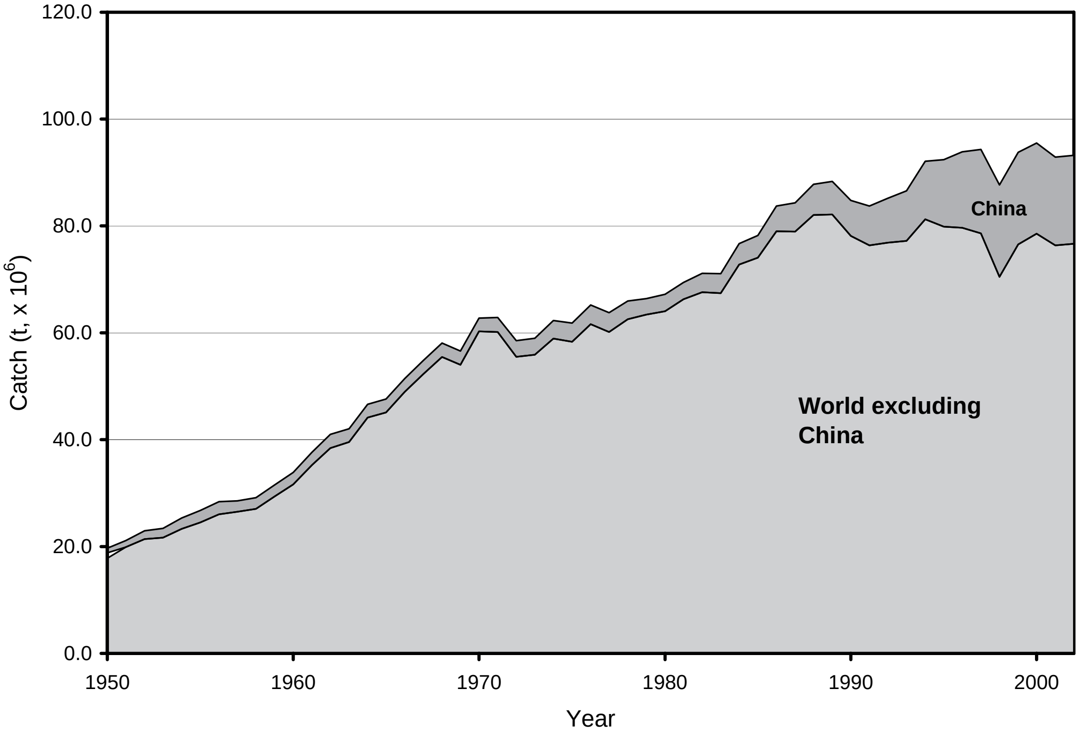

Fig. 31 Total catch (in millions of t) for China, and the world, excluding China, in capture fisheries from 1950 to 2002 (FAO data).

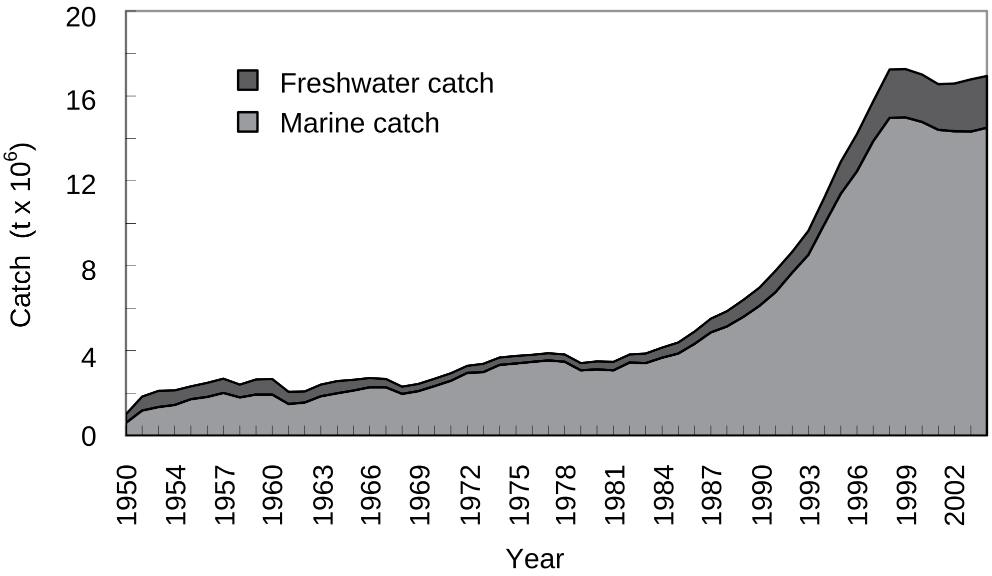

Fig. 32 Contributions of marine and freshwater catches to the total Chinese capture fishery.

Table 22 Major species and their percentages in biomass (weighted from May, August and October) of fisheries resources, by year, in the Bohai Sea (modified from Tang *et al.*, 2003).

Species	**%**
1959	
Small yellow croaker *Pseudosciaena polyactis*	29.5
Largehead hairtail *Trichiurus haumela*	29.3
Peneaid shrimp *Penaeus chinesis*	14.6
Half-fin anchovy *Setipinna taty*	4.7
Skate *Roja porosa*	4.4
1959 Total Marine Catch	82.5
1982	
Half-fin anchovy *Setipinna taty*	20.3
Squid *Loligo beak*	10.7
Blue crab *Portunus trituberculatus*	10.3
Anchovy *Engraulis japonicus*	7.7
Small yellow croaker *Pseudosciaena polyactis*	5.6
Spanish mackerel *Scomberomorus niphonius*	4.3
Mantis shrimp *Oratosquilla oratoria*	4.1
Seabass *Lateolabrax japonicus*	3.3
Skate *Roja porosa*	3.0
Yellow drum *Nibea albiflora*	2.7
Scaled sardine *Harengula zunasi*	2.5
Pomfret *Stromateoides argenteus*	1.8
White croaker *Argyrosomus argentatus*	1.6
Bighead croaker *Collichthys niveatus*	1.4
Southern rough shrimp *Trachypenaeus curvirostris*	1.4
Cuttlefish *Sepiella maindroni*	1.4
1982 Total Marine Catch	82.1
1992–1993	
Anchovy *Engraulis japonicus*	35.1
Half-fin anchovy *Setipinna taty*	10.1
Gizzard shad *Clupanodon punctatus*	8.2
Small yellow croaker *Pseudosciaena polyactis*	7.2
Mantis shrimp *Oratosquilla oratoria*	6.1
Squid *Loligo beak*	5.9
Blue crab *Portunus trituberculatus*	3.6
Seabass *Lateolabrax japonicus*	3.4
Rednose anchovy *Thrissa kammalensis*	3.3
Skate *Roja porosa*	3.2
1992–1993 Total Marine Catch	82.5
1998	
Gizzard shad *Clupanodon punctatus*	24.0
Half-fin anchovy *Setipinna taty*	18.1
Pomfret *Stromateoides argenteus*	11.1
Spanish mackerel *Scomberomorus niphonius*	8.5
Mantis shrimp *Oratosquilla oratoria*	5.7
Blue crab *Portunus trituberculatus*	4.8
Rednose anchovy *Thrissa kammalensis*	4.8
Small yellow croaker *Pseudosciaena polyactis*	4.0
1998 Total Marine Catch	81.0

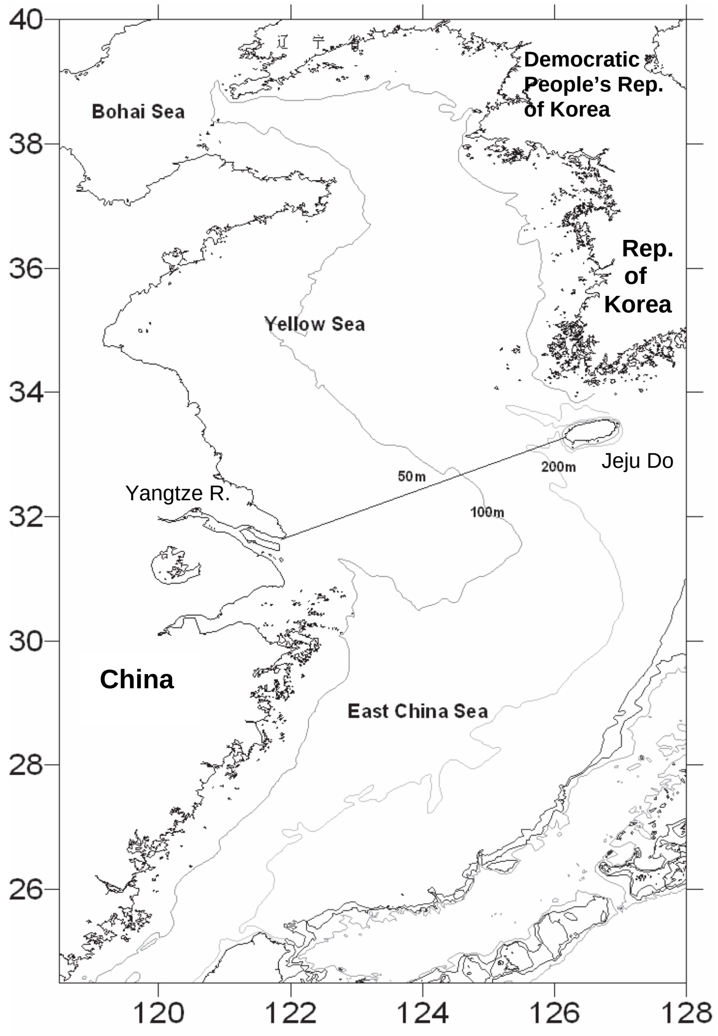

Fig. 33 Map of East China, Yellow and Bohai seas. Line between the Yangtze River and Jeju Do denotes the division between the Yellow Sea and East China Sea.

Climate

The climate system of the Yellow Sea and East China Sea is strongly affected by processes in the Northwest Pacific Subtropical High system through the Kuroshio Current and the land climate system. The Asian monsoon is dominant in the summer, and the northern cold air system is important in the winter months. Therefore, the long-term variation in the East China Sea and the Yellow Sea is complex. Both seas share the same climate system. Air temperature over the area has followed a warming trend since 1956. A negative temperature anomaly period occurred from 1956 to 1987, followed by a positive anomaly until 1998. Since 1998, it appears that there is a negative temperature anomaly. Wang *et al.* (1998) considered that air temperature patterns differ from large-scale global patterns because of the influence of climate over the land. There was a warming of the Yellow Sea sea surface from 1989 until 2000, when a cooling period began. In general, there has been a warming trend since 1968, with an increase in sea surface temperature of 0.27°C per decade and 0.12°C per decade at 50 m depth. In the East China Sea there has been a decadal pattern in the coastal sea surface temperatures. In general, the 1960s were cool, the 1970s warm, the 1980s cool, and the 1990s warm, with a maximum occurring around 1998. Temperature increases in coastal areas were larger than in offshore areas.

Key Species in the Fishery

Small yellow croaker (*Pseudosciaena polyactis*)

Biology

Small yellow croaker is warm-temperature bottom fish that is distributed in the Bohai Sea, Yellow Sea and East China Sea (Zhao *et al.*, 1990). Three geographical stocks, the northern stock, the Lüsi stock, and East China Sea stock, are recognized (Liu, 1990). The northern stock migrates seasonally between the central southern Yellow Sea during winter and northern part of the Yellow Sea and Bohai Sea from spring to autumn. The Lüsi stock is the largest and is distributed in the southern Yellow Sea. It migrates seasonally, often only short distances, mainly between shallow and deep waters in the southern Yellow Sea. The East China Sea stock only migrates in the East China Sea waters.

In the Yellow Sea small yellow croaker mainly over-winter in water depths of 60 to 80 m. Water temperatures range from 8° to 15°C and salinity varies from 33 to 34 psu. Spawning grounds are usually in the estuaries where the salinity is affected by river runoff. Small yellow croakers start their spawning migration from the wintering grounds in March, and spawn in the shallow coastal waters of 10 to 20 m depth from April to May, mostly along the Chinese coastal waters. In the 1950s and 1960s, about 0.5 to 3% of 1-year-old fish were mature and most fish matured at 2 years. However, most fish have matured at 1 year since the mid-1970s. The fecundity of small yellow croaker is from 32,000 to 72,000 eggs per fish at age 2 to 4 years and from 83,000 to 125,000 eggs per fish at age 5 to 9 years. Population parameters of small yellow croaker in the northern area during April surveys from 1955 to 1998 are presented in Table 23.

Small yellow croaker is a slow growing species with a long life span, and a maximum recorded age of 23 years (Liu, 1990). The northern stock in the waters off northern Shandong Peninsula in spring is comprised of fish migrating into the spawning grounds of the Bohai Sea from the wintering grounds of the central Yellow Sea. This population has been traditionally fished by fishermen from northern China in April. During the late 1950s, the length composition in catches ranged from 19.7 to 21.9 cm in mean body length and 150 to 199 g in mean body weight, and consisted mainly of age groups from 2 to 5 years. Fish below 16 cm in body length, being mostly immature, occupied only a small proportion of the spawners in the 1950s. From 1955 to 1957 this proportion was only 1.0 to 3.9%, increasing slightly in 1958 and 1959 because of the great exploitation pressure in 1957. Consequently, the proportion of young fish increased in the spawning population after 1957 (Liu, 1960). Meanwhile, fish over 20 cm body length accounted for 51.2 to 85.8% of the population. Therefore, the older fish, which could repeat spawning, became the major source of spawners, indicating that the stock was not out of equilibrium. After about three decades of heavy exploitation, the population structure changed. Compared to the 1950s, the fish size of the northern area stock in the 1980s was smaller, only 15.1 to 16.6 cm in mean body length and 59 to 80 g in mean body weight (Table 23). The smallest mean fish size in the 1980s occurred in 1985, and increased slightly in 1986. During the surveys of the 1980s, the number of small yellow croaker below 16 cm body length accounted for 54.3 to 76.5%, and those larger than 20 cm accounted for 8.5 to 17.2% of the catch. This trend was almost opposite to the situation observed in the 1950s. Only 8.5% over 20 cm, 15% in the range of 17 to 19 cm, and the rest below 16 cm in body length were found in the catch of 1985. Thus, only a minor proportion of the stock may be able to spawn more than once before being caught.

The mean length of the spawning population of the Lüsi stock in spring is shown in Table 24. During the 1950s and 1960s, the mean length of the stock ranged from 20.0 to 24.4 cm, with a corresponding mean body weight of 140 to 318 g and mean age of 3.8 to 6.3 years, older than observed for the northern stock. In the 1970s, the number of older fish decreased with a corresponding increase in fishing intensity, which affected the whole structure of the stock. Mean body length declined to 17.9 cm with a mean body weight of 102 g and a mean age of 2.4 years. In the 1980s, the structure of the spawning population continued to change. Fish in the catches of the Lüsi stock in the main distribution area averaged only 14.7 cm in length, 55 g in body weight and had a mean age just exceeding 1 year. The catch in 1985 had a mean length of only 12.7 cm and 35 g in mean body weight, increasing in 1986, but then decreasing to the smallest values ever recorded in 1987 and 1988 (Table 24). The Lüsi spawning stock in the spring was comprised of mainly 1- to 2-year-old fish, of which the 1-year-olds were dominant. Older fish were rarely caught in the 1980s. Therefore, in recent years the spring fishery has been highly dependent on recruiting year classes.

Fishery

The population which was distributed in the wintering grounds (far from shore) was rarely fished in the 1950s because of small-sized fishing boats and rough seas. However, with improvements to fishing vessels and gear technology, fishermen can now fish in all areas of the Yellow Sea year round, so that small yellow croaker is also fished/exploited heavily during the winter months.

Small yellow croaker in the Yellow and Bohai seas were mainly exploited by China, Japan and Korea in the 1950s and 1960s. Since the 1980s, this species has been fished mainly by China and Korea. In China, small yellow croaker are caught mostly by the three northernmost provinces (Shandong, Liaoning and Hebei) and one municipality (Tianjin), and some catches are also taken by the Jiangsu province and Shanghai in the mid-eastern part of China.

Figure 34 shows the fluctuation in catch of small yellow croaker by northern China from 1950 to 1998 (Jin, 1996a,b). This catch might be slightly different from the actual catch from the Yellow and Bohai Seas due to the incomplete statistics, but it reflects the variation in catch of small yellow croaker in the Yellow and Bohai Seas during this period. The yield of small yellow croaker increased nearly linearly in the 1950s, and tended to decline in the 1960s, reaching the lowest level in 1972. Since then, the catch has varied with several small peaks, but increased continuously in the 1990s, perhaps indicating a trend of increased productivity.

During the 1960s, the total fishing power of northern China, as reflected by the increased horse power of motor boats, expanded by more than three times. Motorboat horsepower in the 1970s and 1980s increased 10 times and 24.5 times, respectively, compared to the 1950s. Although the fishing effort cannot be proportionately allocated to small yellow croaker, the fishing pressure has undoubtedly risen considerably.

Table 23 Size composition and mean body length, weight and major age groups of small yellow croaker in the north area northern Yellow Sea in spring from 1955 to 1998 (Jin, 1996a).

Year	$\bar{L}$ (cm)	$\bar{W}$ (g)	Main age group (yrs)	Percentage of length group by number		
				≤ 160	170–190	≥ 190
1955	21.9	199	3–5	1.0	13.2	85.8
1956	21.7	191	2–5	2.4	22.2	75.4
1957	20.8	163	2–4	3.9	35.4	60.7
1958	19.7	157	2–3	14.9	33.9	51.2
1959	19.8	150	2–4	17.7	27.6	53.9
1985	15.1	59	1–2	76.5	15.0	8.5
1986	16.6	80	1–2	54.3	28.7	17.0
1988	16.5	78	1–2	54.5	28.3	17.2
1998	12.3	28	1	100	0	0

Table 24 The mean body length, weight and age of the pre-spawning population (spring) of small yellow croaker in the southern Yellow Sea from the 1950s to 1980s (Jin, 1996a).

Year	1950s	1960s	1970s	1980s	1980	1985	1986	1987	1988
$\bar{L}$ (cm)	22.1	22.7	17.9	14.7	16.4	12.7	15.9	12.1	12.3
$\bar{W}$ (g)	203	218	102	55	77	35	70	30	31
$\bar{t}$ (yr)	5.3	5.2	2.4	1.2	1.5	0.8	1.4	0.6	0.7

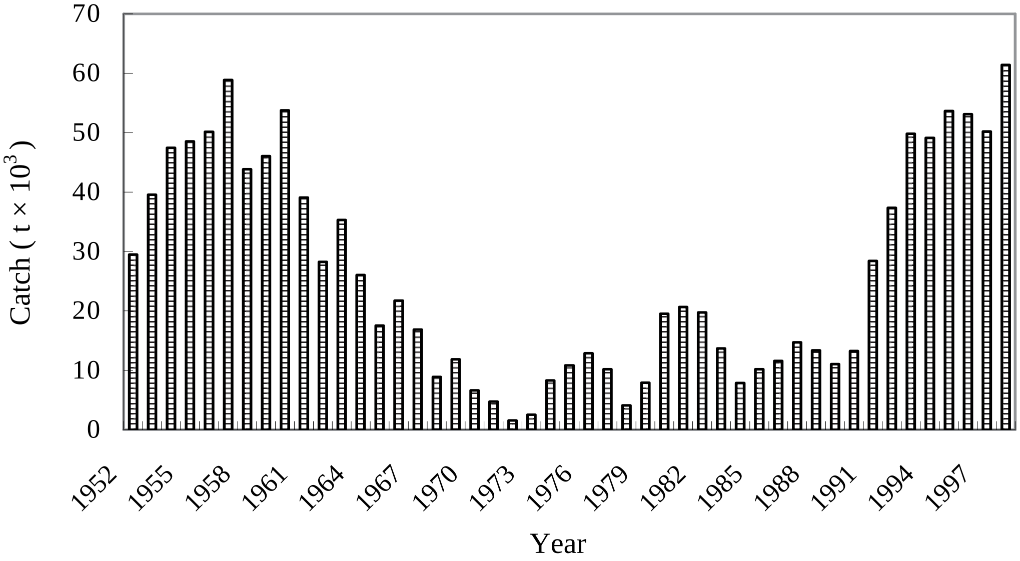

Fig. 34 Variations in catch of small yellow croaker from northern China from 1950 to 1998.

The proportion of small yellow croaker in the catches of marine fishes in northern China varied from 14.0% in the 1950s to 7.6% in the 1960s, 1.2% in the 1970s, and 2% in the 1980s. The proportion increased in the 1990s, indicating that the species productivity may have started to improve.

Ocean and climate effects

Small yellow croaker is a bottom fish that also spawns on the bottom. Kim *et al.* (1997) showed that cold temperatures at 75 m depth were associated with reduced productivity and weak year classes. From 1989 through to 2000, there was a warming period in the Yellow Sea, after which a cooling period began. It is difficult to assess the impact of ocean and climate changes in the species. Small yellow croaker is a migratory fish with a wide temperature range, and abundance data are obtained from the fishery which depends on fishing effort.

There was no indication of major environmental changes in the Yellow Sea in the 1980s when catches declined to one-sixth of those in the 1960s (Tang, 1993), which suggests that the decreases resulted from excessive fishing. Despite these drops and very high fishing effort, there was a recovery of the catch in the 1990s, suggesting that trends in the ocean environment were associated with the increased abundance.

Anchovy (*Engraulis japonicus*)

Biology

Anchovy is a small inshore pelagic species that is widely distributed in the Bohai Sea, Yellow Sea, and East China Sea. There may be at least two stocks in these areas: Yellow Sea and Bohai Sea stock and East China Sea stock (Zhu and Iversen, 1990). Anchovy migrate seasonally with changes of sea surface temperature. The optimum temperature ranges from 10° to 13°C, and the anchovy is not usually found in waters below 7°C (Iversen *et al.*, 1993). In November and December, the densest areas of distribution are in the northern and central parts of the Yellow Sea. During winter anchovy migrate to the southeastern region of the Yellow Sea and northern part of the East China Sea. In spring, as water temperatures increase and anchovy gonads develop, the fish migrate into shallow coastal waters for spawning, and then disperse for feeding, moving into deeper southern waters. After November, there are very few anchovy left in the Bohai Sea. Dense schools are observed in the southeastern Yellow Sea and northern East China Sea. Anchovy also migrate diurnally, depending on the light and water temperatures. They usually appear in dense schools near the bottom during the daytime, and remain scattered in the upper to surface layers at night.

Spawning areas are in the nearshore waters and bays along the Chinese coast. The three major spawning areas are: bays in the Bohai Sea, nearshore waters off the southern tip of the Shandong Peninsula, and off the Zhejiang (East China Sea) coast (Zhang, 1983; Zhu and Iversen, 1990). The age of anchovy at first maturity is 1 year. Fecundity ranges from 600 to 13,600 eggs per female.

According to the surveys by the R/V *Bei Dou* from 1984 to 1988 (Zhu and Iversen, 1990), the spawning season of anchovy is from May to October. The peak spawning period is from mid-May to late June, with the optimum spawning temperatures from 14° to 18°C in the Yellow Sea. One- to 2-year-old fish dominate the spawning stock. Ovulation can be of the multi-peak or continual type, within a year, *i.e.*, ovulation occurs as the eggs ripen, without an obvious resting stage in between (Li, 1987).

There are some feeding differences between juveniles (0 age group) and adults. The diet of juvenile anchovy is dominated by copepoda (55% by weight; Chen, 1978; Zhu, 1991). As the anchovy grow, the dominant prey gradually shifts to the arrow worm *Sagitta crassa*, copepod *Calanus pacificus*, amphipod *Themisto gracilipes*, euphasiid *Euphausia pacifica*, and some algae.

The length of anchovy at hatching ranges from 2.6 to 2.9 mm (Zhao *et al.*, 1990). Zhang (1983) reported that the body length was 3.2 mm after hatching, and at a body length of 18.5 mm (length at metamorphosis), it becomes an adult. Five months after spawning, the length reaches 60 to 90 mm. The growth rate is higher for the 1-year-old group, and is reduced with age (Zhu and Iversen, 1990). The maximum life span is about 4 years (Iverson *et al.*, 1993). Anchovy are prey for 30 to 40 important higher trophic level species (Tang and Ye, 1990).

Fishery

Anchovy used to be an undesired species for the Chinese fishery because of its low market value. In the past, only post-larvae and juveniles were used by some coastal artisan fishermen for dried food. In the 1960s, the catch was very small, about 750 to 1000 t in the northern Yellow Sea. In recent years, a dramatic increase in biomass occurred in the Yellow Sea and northern East China Sea. The stock seemed to be stable and was estimated by acoustic surveys to be about 2.5 to 4.2 million t (Zhu and Iversen, 1990) from 1985 to 1995. A potential annual catch was on the order of 0.5 million t (Iversen *et al.*, 1993). In 1989, a pair-trawler anchovy fishery started and expanded quickly into a large-scale, year-round fishery in the mid-1990s. Since then, there has been a rapid decline and by 2001–2002, the abundance was less than 10% of its peak level in 1993, which was estimated to be 4,120,000 t (Zhao *et al.*, 2003).

The annual anchovy catch in China varied between 30,000 and 190,000 t between 1989 and 1992. It rapidly increased to 600,000 t in 1996, more than 1 million t in 1997 and 1998, and has decreased thereafter (Fig. 35). Intense fishing, increasing yearly by 20 to 83% in catch in the Yellow Sea before 1999, must have affected the spawning stock because the fishery has shown a considerable increase in the proportion of 1-year-old fish. More than 90% of the catch from the Yellow Sea was recruitment from the spring of 1998, and acoustic surveys show that the stock is now almost collapsed (Jin *et al.*, 2001).

Climate and ocean effects

There is evidence that the abundances of Japanese anchovy and Japanese sardine follow opposite trends. This indicates that ocean conditions are responsible for the shifts in trends from one species to another. Kim (1992) proposed that the distribution of anchovy eggs and larvae in June is related to the ocean conditions in the eastern waters off Korea. Ocean conditions that favour the transportation of anchovy eggs and larvae into productive coastal areas in the summer also favour anchovy survival and growth.

Spanish mackerel (*Scomberomorus niphonius*)

Biology

Spanish mackerel are widely distributed in the northwestern Pacific Ocean. They are abundant in the Bohai, Yellow, and East China seas. The species undergoes long-distance seasonal migration. There are two wintering stocks, one in the southeastern Yellow Sea, and the other located offshore of the East China Sea (28°00′–31°20′N, 123°40′–125°30′E). The stock in the East China Sea spawns from April to May, mainly in the coastal waters between Fujian (southeast China) and the Shandong Peninsula. The other stock spawns from May to June in the Bohai Sea and the northern Yellow Sea (Wei, 1991). After spawning, Spanish mackerel feed in

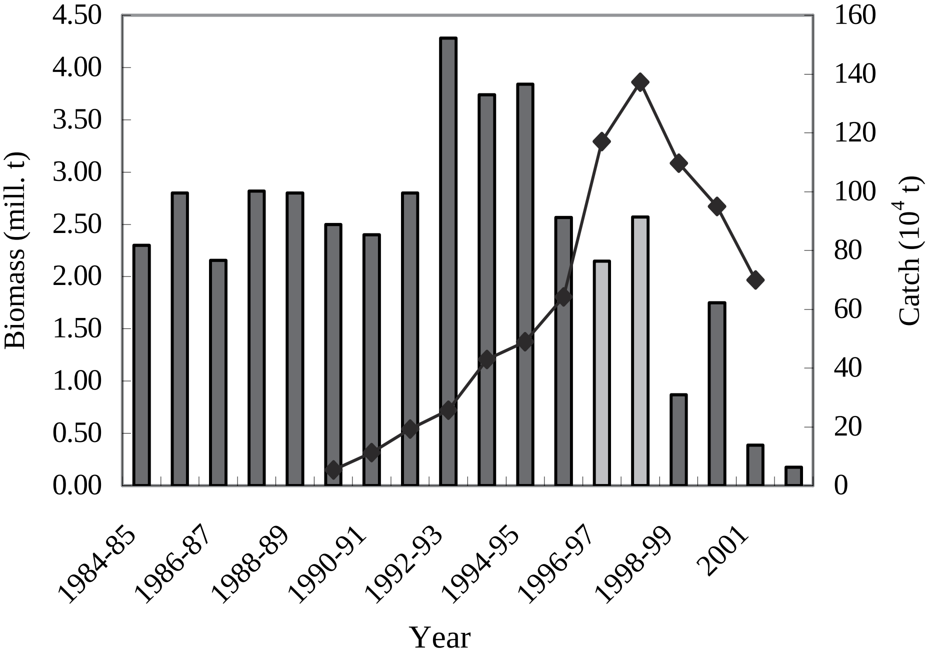

Fig. 35 Yearly variations of Japanese anchovy biomass (bars) and landings (line). Biomasses in 1997 and 1998 were estimated by virtual population analysis (VPA); catches in 2000 and 2001 were estimated.

coastal waters. The distribution of this species is strongly influenced by water temperature. They migrate southward with decreasing temperatures. In November, they are distributed mainly in the central and southern Yellow Sea and in December, return to their wintering grounds.

Spanish mackerel mature at 1 to 2 years in the Yellow and Bohai seas. They spawn mostly in the bays of the Bohai Sea, although some spawn along the coast of Shandong Peninsula. The major spawning season is from May to June, depending on the water temperature. Spawning occurs at a depth of 15 to 30 m. The water temperature of the spawning areas differs greatly between the northern and southern waters, ranging from 9° to 13° C in the Bohai Sea and 11° to 20°C in the southern East China Sea, whereas the salinity is similar throughout, ranging from 28 to 31 psu (Zhang, 1983; Wei, 1991). Fecundity is about 280,000 to 1.1 million eggs per female.

Spanish mackerel are believed to have strong piscivorous habits. Small pelagic fish, such as Japanese anchovy and sardines, account for about 90% of the total weight of their stomach contents (Tang and Ye, 1990). Japanese anchovy make up the larger portion and have been referred to as “food of Spanish mackerel” by Chinese fishermen. The size of prey increases with the growth of Spanish mackerel, but the prey composition does not vary significantly.

At hatching Spanish mackerel measure from 4.3 to 5.0 mm in fork length (Zhao *et al.*, 1990). Their growth rate is the fastest recorded among pelagic fishes in the Yellow and Bohai seas. Ocean age 0 fish can reach 25 to 30 cm in fork length and weigh 200 to 400 g at the time of spawning. Females grow faster than males, with an average increase in length of 26.1%, compared with 21.9% for males in the second year after spawning (Wei, 1991).

Fishery

Spanish mackerel are the largest fishable pelagic fish in the Yellow and Bohai seas. In autumn, there is no obviously dominant length group, as fork length can range from 20 to 54 cm. Ocean age 0 fish account for 99.7% of the catch. Mean lengths have decreased since the mid-1960s, indicating an increased proportion of young fish. Age 1 fish accounted for only 1 to 7% during the period from 1952 to 1969, increased to 10–27% in the 1970s, and further increased to about 36–56% in the beginning of the 1980s (Wei, 1991).

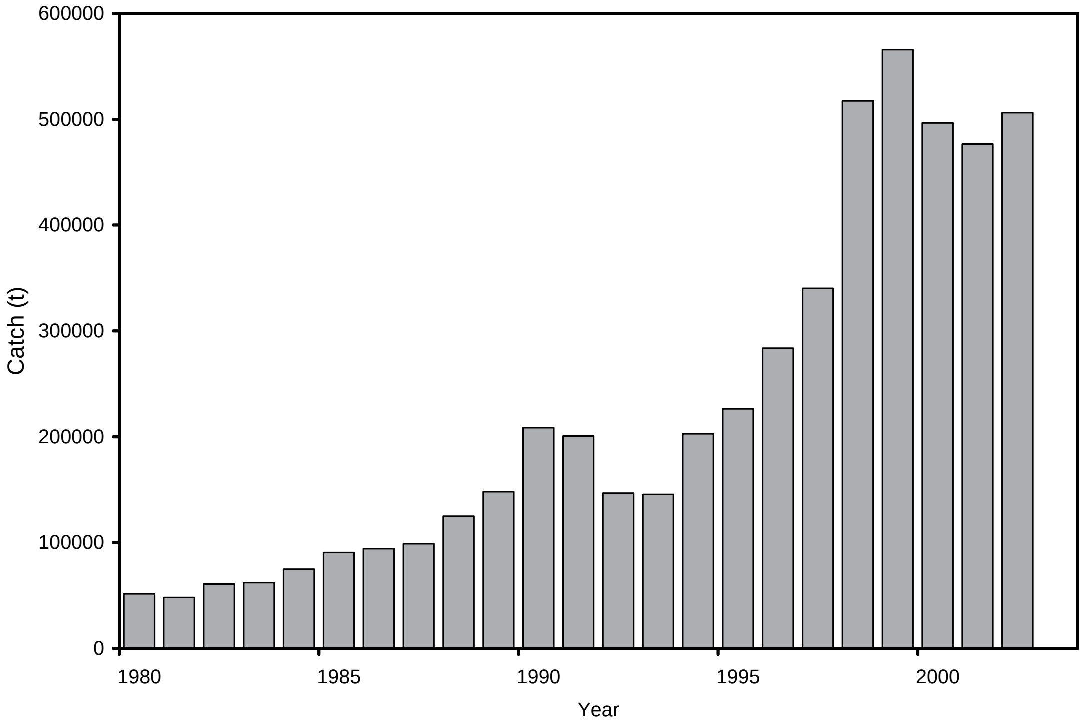

Fig. 36 Chinese catch (t) of Spanish mackerel from 1980 to 2002 (FAO, 2003).

Spanish mackerel are caught mainly by gillnet in China, and are a bycatch in other fisheries. The annual catch increased rapidly in the 1960s and ranged from 20,000 to 40,000 t. Two-year-old fish dominated the catch (about 75%), and the total mortality was about 65% (Wei, 1991). By the mid-1970s, the catch was taken mainly from the spawning stock in spring. Thereafter, the increase in fishing effort and the large quantity of age 0 fish caught by trawlers in autumn have resulted in a decline of spring catch. Total catches from northern China fisheries have continuously increased in recent years, reaching more than 500,000 t (Fig. 36). Since the mid-1990s, the catches have occurred mainly in the autumn, following the summer fishing closure.

Climate and ocean effects

It is difficult to identify a relationship between climate, the ocean, and productivity because of the lack of time series data.

Pacific herring (*Clupea pallasii*)

Biology

Pacific herring is a local stock that only inhabits the central to northern regions of the Yellow Sea (north of 34°N; Ye *et al.*, 1980). There was a small stock found in the 1950s which became widely distributed in the Yellow Sea from the late 1960s onward. The wintering ground is in the central, deep water of the Yellow Sea. In February the adult population migrates toward coastal waters off the Shandong Peninsula for spawning, and then moves into the central and northern Yellow Sea for feeding. In winter the stock is distributed mainly in the central part of the Yellow Sea (Tang, 1991).

Spawning begins in February in very shallow waters (3 to 7 m) along the coast and bays around the Shandong Peninsula, with a small group of herring spawning on the banks in the northern Yellow Sea and off western Korea. The main spawning season is from March to April. Water temperatures of 0° to 5°C and salinity around 30 psu are required for spawning (Zhang, 1983). The eggs stick together and adhere to reefs, algae, and other substances (Tang, 1980). Hatching time decreases with increased temperature, from about 12–14 days at 5.5°–10°C to 7–8 days at 15°–20°C (Jiang and Chen, 1981; Zhang, 1983). According to observations on artificial hatching and embryonic development of Yellow Sea herring (Jiang and Chen, 1981), the body length of newly hatched larvae ranges from 5.2 to 6.8 mm. After 4 to 5 days, they reach 7.2 to 7.8 mm, and after 12 to 13 days, attain a length of 9.9 to 11.2 mm. The growth rate is fastest during summer, accounting for 43% of the total yearly growth, and decreases during autumn (Tang, 1991).

The feeding period is mainly from April to August, and *Euphausia pacifica* constitutes more than 99% of the total stomach contents by weight in Pacific herring in the Yellow Sea (Wei and Jiang, 1992). During the rest of the year they feed little or not at all.

During the spring survey in 1986, the fork length of the spawning stock of Yellow Sea herring ranged from 13 to 30 cm, with a mean length of 20.8 cm. There were two peaks in the length distribution, one at 18–19 cm and one at 23–24 cm, which accounted for 38.8% and 30.9% of 1- and 2-year-old fish, respectively. However, when the stock was very abundant during the period from 1970 to 1974, the mean age of the catch was 2.5 years and the fork length and body weight averaged 22.8 cm and 134 g, respectively. Fish 4 years old and older accounted for 15.6%, and decreased to 1.5% in the period from 1975 to 1982 (Liu, 1990). This demonstrates that the spawning stock at present depends mainly on the 2-year-old age group. In autumn, the length composition of herring was dominated by the 21–22 cm group, accounting for 67.2% by number, and 9.3% of the catch was age 0 fish.

Fishery

The Yellow Sea herring fishery has experienced two peaks in history (around 1900 and 1938), followed by a period of little or no catch (Tang, 1993). Since 1967, many demersal stocks in the Yellow Sea have been overfished or depleted. Recovery and outburst of the Yellow Sea herring seems to be associated with the depletion of other stocks. The catch of Yellow Sea herring increased rapidly to a peak (more than 180,000 t) in 1972, and decreased sharply thereafter. Tang (1981, 1993) demonstrated that although the fluctuations in recruitment of the Yellow Sea herring have been very large and have had a direct effect on the fishable stock, there is no strong relationship between spawning stock and recruitment. Environmental conditions, such as rainfall, wind, and daylight, are major factors affecting the fluctuations in recruitment, and long-term changes in biomass may be correlated with a 36-year cycle of the wetness oscillation in eastern China (Tang, 1993). Undoubtedly, high fishing pressure speeds up the depletion. During a period of declining stock size, the spawning stock must be kept above the biologically safe level. The abundance of adult fish is currently reduced to a very low level, and there is no longer a fishery of this stock in the Yellow Sea.

Climate and ocean effects

Tang (1981, 1987, 1995) found that there was no strong relationship between the size of the spawning stock and subsequent recruitment. Similar observations have been made for other Pacific herring populations. It was observed that rainfall, wind, and daylight affect recruitment. There is also a relationship between periods of abundance and a 36-year cycle of dryness and wetness which is associated with the Southern Oscillation. The trends in Pacific herring catch ae also similar to catches of chub mackerel (Tang, 1995), indicating that ocean conditions affecting Pacific herring recruitment may occur in trends. It is believed (Ye, 1985) that environmental conditions have an important influence on the long-term productivity of chub mackerel.

Pacific herring abundances tend to be controlled by predation and productivity, the so-called “wasp-waist” relationship. If there is abundant food for larval herring, there may be strong year classes. If favourable ocean conditions also produce predators of herring, then the abundances are smaller. Recognizing that these effects may occur, it is also important to recognize that overfishing is an important cause of the collapse of herring in the Yellow Sea.

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The Fishery

There are 300 to 400 fish species in the marine waters around Korea of which over 100 species are of commercial value. Korean fisheries yield over 1 million t of marine fish from the waters annually. In general, the increase in fishing activities since the 1970s has reduced fish populations. UN Food and Agriculture Organization records (FAO, 2000) indicate that total catches of marine fish and invertebrates averaged 1,565,973 t from 1980 to 2000. The largest catch of 2,056,521 t occurred in 1986 (Fig. 37). Catches were relatively stable from 1987 to about 1996, and have decreased slightly in recent years.

Catches in the Yellow Sea and the East China Sea were 210,000 t in the early 1960s. However, they grew rapidly and have exceeded 1 million t since the mid-1970s. Total catches started to decrease after 1986 when they reached around 1.5 million t. Recently catches have been about 1 million t (Fig. 38).

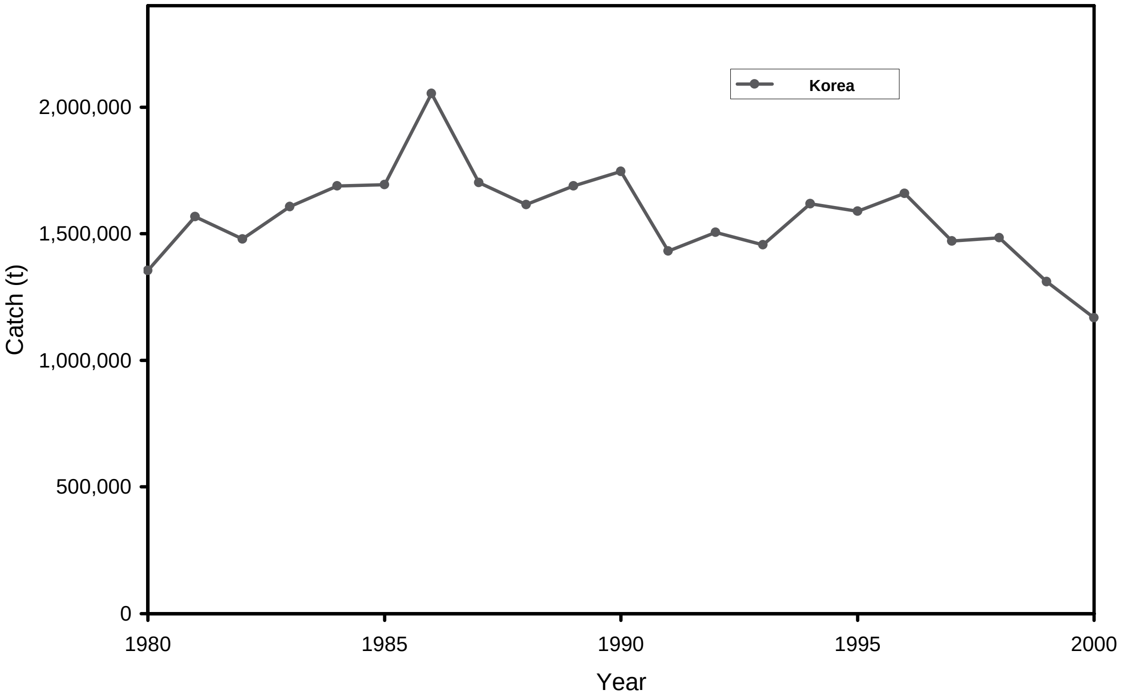


Fig. 37 Total commercial catches of marine fish and invertebrates by Korea since 1980 (FAO, 2000).

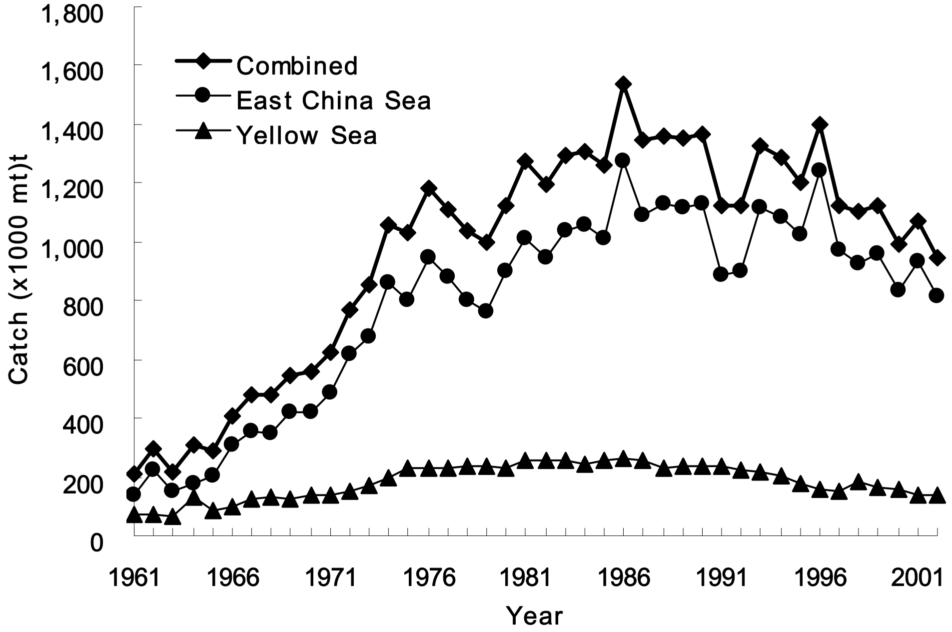


Fig. 38 Annual catch of fish and invertebrates in Korean waters of the Yellow Sea and the East China Sea.

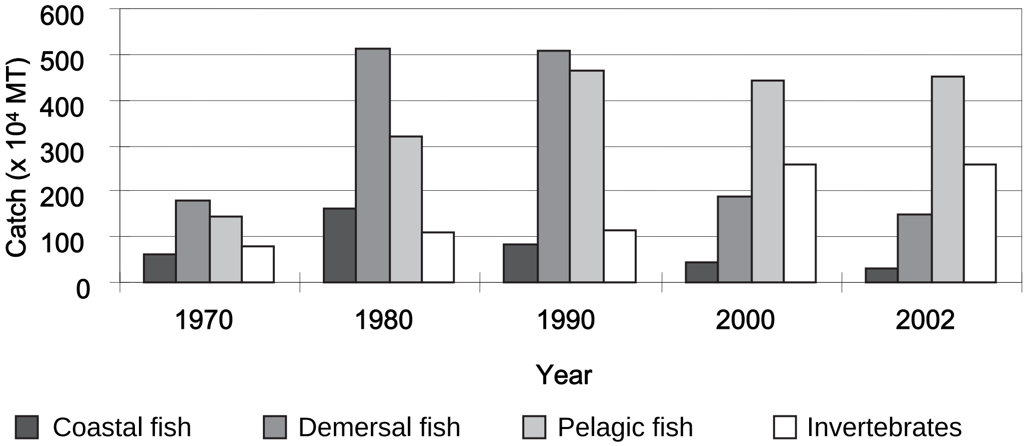


Fig. 39 Catch composition, by group, of Korean fisheries from Korean waters.

From 1980 to 2000, catches in demersal fishes decreased, and increased in pelagic fishes and invertebrates (Fig. 39). Demersal fish used to be abundant in Korean waters and were especially predominant on the Korean side of the Yellow Sea and the East China Sea in the 1960s (Zhang and Kim, 1999). In addition to the decrease in abundance, the size of spawning demersal fish has continuously decreased. The abundance of small pelagic fish has increased in the Tsushima Warm Current system. For example, Japanese anchovy (anchovy hereafter) are widely distributed in the northwestern Pacific Ocean as demersal fish abundance decreased, and are one of the most abundant pelagic species in the Yellow Sea and the East China Sea. Chinese research surveys in the winters between 1986 and 1995 indicated that anchovy biomass fluctuated between 2.5 to 4.3 million t in the Yellow Sea and the East China Sea. However, recent overexploitation and natural decreases appear to have caused the depletion of anchovy stocks on the Chinese side of the Yellow Sea. Other small pelagic fish, including the common squid, have tended to increase, occupying about 70% of the total catch of Korean marine fisheries.

The seven major target species in the Yellow Sea during the last 40 years are: (1) largehead hairtail (hairtail hereafter), (2) corvenia, (3) anchovy, (4) small yellow croaker, (5) blenny, (6) pomfret, and (7) flounder. Species composition in the catch has changed remarkably during the 1960s to 1990s. Hairtail were most dominant, followed by small yellow croaker in the 1960s and 1970s. Thereafter, the catch of small yellow croaker decreased while corvenia, flounder, and anchovy increased in the 1980s and 1990s (Fig. 40).

The seven major target species in the East China Sea during the last 40 years are: (1) anchovy, (2) chub mackerel, (3) threadsail filefish (filefish hereafter), (4) hairtail, (5) Japanese sardine, (6) corvenia, and (7) common squid. Anchovy, hairtail, and small yellow croaker dominated in the 1960s, but the catch of small yellow croaker almost disappeared from the composition after the 1960s. The relative

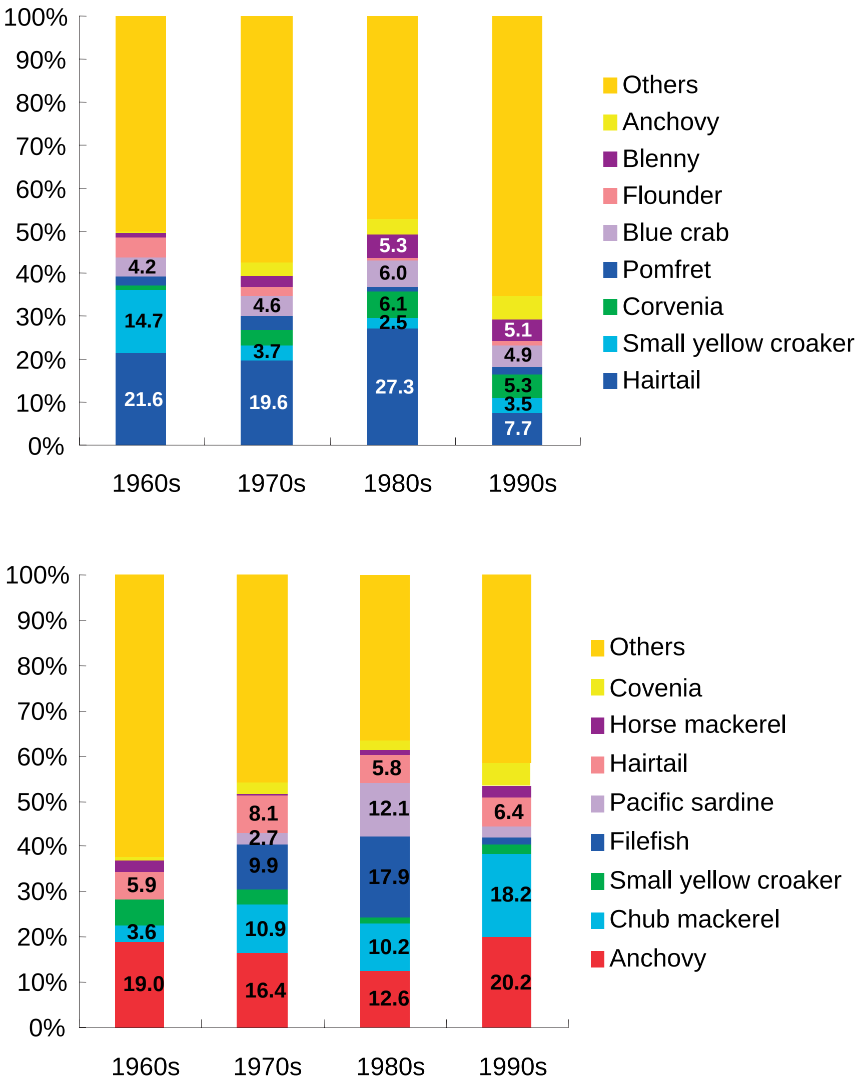


Fig. 40 Catch proportions by species from 1961 to 2000. Yellow Sea (upper panel) and East China Sea (lower panel).

compositions of chub mackerel, filefish, and sardine increased in the 1970s and the 1980s. In the 1990s, filefish and sardine disappeared and anchovy, chub mackerel, and common squid dominated the composition (Fig. 40).

Around 350 to 400 fish species reside in the East/Japan Sea (which also is called the Japan/East Sea, the East Sea, the Sea of Japan, or the Japan Sea). In the waters of the northern Korean Peninsula, demersal species represent 75% of all species and the ratio of demersal species decrease to 45% in the waters of the southern Korean Peninsula. Pelagic fish are greater in the south than in the north. Total commercial catch by neighboring nations in the East/Japan Sea peaked in 1983, reaching 3.3 million t. Korean catches, however, ranged from 132,000 t in 1967 to 275,000 t in 1982. The major species were common squid, walleye pollock (also called Alaska pollock, pollock hereafter), and saury, though large fluctuations on the decadal scale have appeared during the last four decades.

Commercial catches in the East/Japan Sea indicate changes in species composition (Fig. 41). The ecological shift between small pelagic fish and demersal fish is especially evident in accordance with the climate regime shift. In the 1960s, common squid catch occupied 43% of the catch in the East/Japan Sea, followed by Pacific saury (15%) and pollock (13%). Pollock increased, accounting for 33% from the 1970s to the 1980s. Concurrently, the proportions of common squid and saury greatly decreased in the 1970s and the 1980s. The dominant fisheries catch also shifted from saury, cod, and pollock in the 1980s to squid in the 1990s (Park *et al.*, 1998). Common squid became the dominant species (45%), and pollock and saury occupied less than 5%. However, knowledge concerning the East/Japan Sea and its relationship to the regime shift has been very limited. Thus there is a strong possibility that an increase in the squid catch is closely associated with changes in the lower trophic levels, such as zooplankton biomass and community structure.

The trophic levels of fishery resources in the catches from Korean waters showed a significant decreasing trend from 1967 to 2000 (Fig. 42). Mean trophic levels were 3.43 and 3.46 in the Yellow Sea and the East China Sea, respectively, during the 1967 –2000 period. Figure comparison shows that the slope of the declining line was steeper in the Yellow Sea than in the East China Sea. Because of the decrease of demersal fish such as small yellow croaker, which are at higher trophic levels, small pelagic fish such as anchovy, common squid, and blenny, which were at relatively lower trophic levels, increased during the four decades.

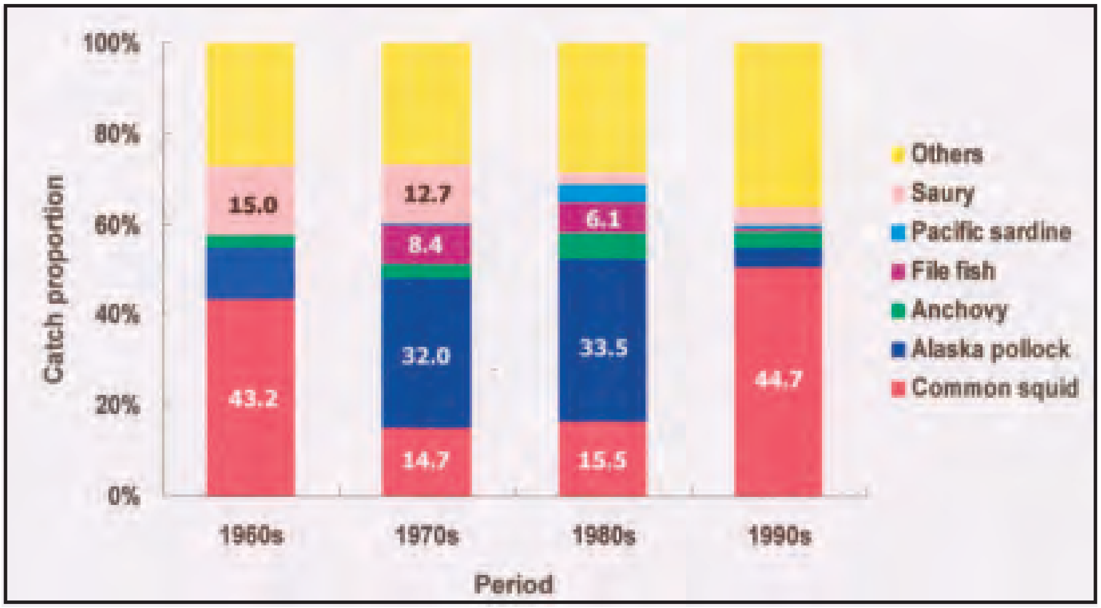


Fig. 41 Catch proportions of major species in the East/Japan Sea from 1961 to 2000.

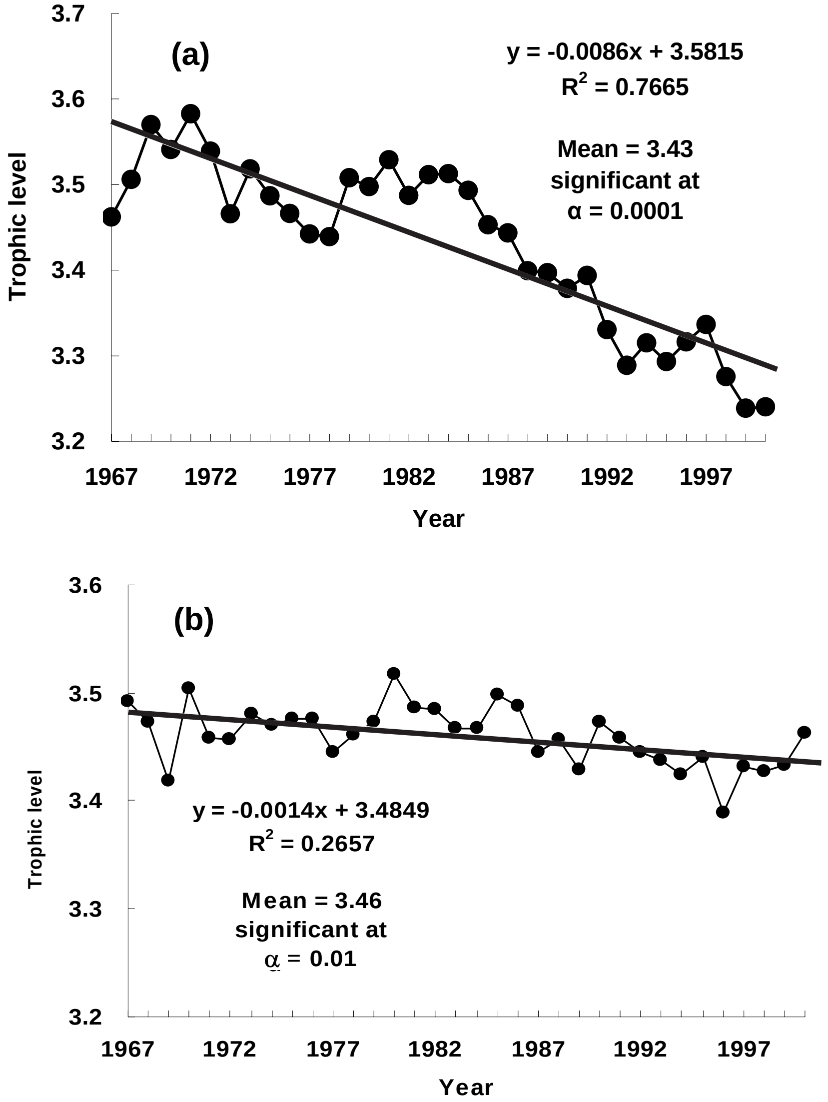


Fig. 42 Catch for mean trophic levels of fishery resources in (a) the Yellow Sea and (b) the East China Sea.

Regime shifts particularly affect the production of major small pelagic fish. Different fishing grounds of common mackerel, horse mackerel, and sardine were found between pre- and post-climatic regime shifts. There were many changes in the East/Japan Sea ecosystem after the 1976/77 regime shift, as seen through changes in the marine environment. In the East/Japan Sea, the mean trophic level increased from 3.09 to 3.28 during the 1976/77 regime shift period (Zhang *et al.*, 2004).

Climate and Ocean Influences

The Korean Peninsula is surrounded by the Yellow Sea to the west, the East China Sea to the south, and the East/Japan Sea to the east. Large-scale air–sea interaction in the Pacific Ocean is the main driving force controlling the climate over the Korean Peninsula. Some effects of climatic events, such as global warming, atmospheric circulation patterns, climate regime shifts in the North Pacific, and El Niños in tropical Pacific waters occasionally appear in this region (Kang *et al.*, 2000; Kim and Kang, 2000; Zhang *et al.*, 2000; Zhang and Lee, 2001).

The Korean Peninsula is located 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 western subtropical Pacific bring heavy rains in the summer and autumn. On the average, about nine typhoons pass through the region every year (Kim and Khang, 2000).

The coastal zone serves as spawning and nursery grounds for fish species, and the survival of some migratory species are threatened by coastal development. The main threat to the coastal habitats is land reclamation, especially in estuaries and shallow bays. During the 1987–1997 period, approximately 25% of the total tidal flats were lost to reclamation in Korea (Cho, 2001). The loss of spawning grounds, and habitat degradation due to pollutants, are also reducing the productivity of the coastal area.

Changes in the sea surface layer in the spring have a profound effect on productivity. There has been a 1.8°C increase in sea surface temperature (SST) in February in the Korean seas during the past 100 years (Hahn, 1994). The rate of change has become greater during the past decade. Hahn (1994) also showed that there was a northward movement of isothermals during the same period (Fig. 43). Aside from the long-term view of global warming, SST is closely related to the variation of the Asian monsoon. The SST change over Korean waters is also connected to the El Niño–Southern Oscillation (ENSO), with phase lags of 5 to 9 months (Park and Oh, 2000) which results in a cold summer in the East/Japan Sea after an El Niño winter.

In the surface layer of the East/Japan Sea, warm water masses were prevalent during the 1960s to 1975, cold ones from 1976 to 1986, and warm ones again since 1987 (Fig. 44). This phenomenon was typical in the spring and the autumn and showed a similar trend, with an exception from 100 to 200 m depth during the late 1970s. It is also anticipated that changes of SST due to climate variability could change the pattern of frontal and current systems in the East/Japan Sea.

Since the early 1990s, high SSTs have prevailed in the East/Japan Sea. Concurrently, zooplankton biomass and catch of warm-water pelagic species (*e.g.*, squids, jellyfish, mackerels) have increased. Recently, the occurrence of warm-water species has been frequently reported, while cold-water species (*e.g.*, pollock) have decreased. The returning rate of chum salmon, which were released from the east coast of the Korean Peninsula, has been depressed. As long as the warming trend of SST continues, more warm-water species (also less cold-water species) are expected to be found in Korean waters.

The spatial distribution of seawater temperature indicated that the isotherms were perpendicular to the coastline at the surface. Those lines, however, became parallel at 50–100 m depth. Especially, during the spring from 1976 to 1986, cold temperatures were prevalent near coastal areas. Warming of seawater was frequently observed from the late 1980s. The vertical structure of temperature represented the cold regime lower than 11°C in the 0 to 100 m layer during the 1977–1983 period. Temperatures warmer than 11°C were common after 1989.

General Description of Ecosystem Status and Fisheries Trends

Changes in Ecosystem Components

In the East/Japan Sea, there was a major change in the ecosystem structure and productivity from 1960 to 1990. The mixed layer depth increased from 1977 and fluctuated around depths about 40% deeper than prior to 1976 (Zhang *et al.*, 2000). The mean transparency depth from Secchi disk observations showed 11.9 m during the 1960–1975 period, but increased to 14.2 m during the 1976–1990 period. This resulted in higher primary productivity (and consequently the zooplankton biomass) appearing in the earlier period (Kang *et al.*, 2000). Correlation studies indicate that some fish (saury and sandfish) predominated the catches when the Southern Oscillation Index (SOI) was positive (*i.e.*, la Niña period), when spring chlorophyll was high, when air temperatures were cooler in coastal cities, and when catches were low for other fish species (sardine and pollock) (Kang *et al.*, 2000; unpublished ms).

Some resident fish species are found near the coast, while others show a long-range migration behavior during the course of spawning. Kim (2003) identified three important ecosystems in Korean waters based on marine commercial fish catches (Fig. 45): 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 the Kuroshio) from the East China Sea to the East/Japan Sea, and the demersal ecosystem in the northern part of the East/Japan Sea. Most species in these categories generally showed a typical migration

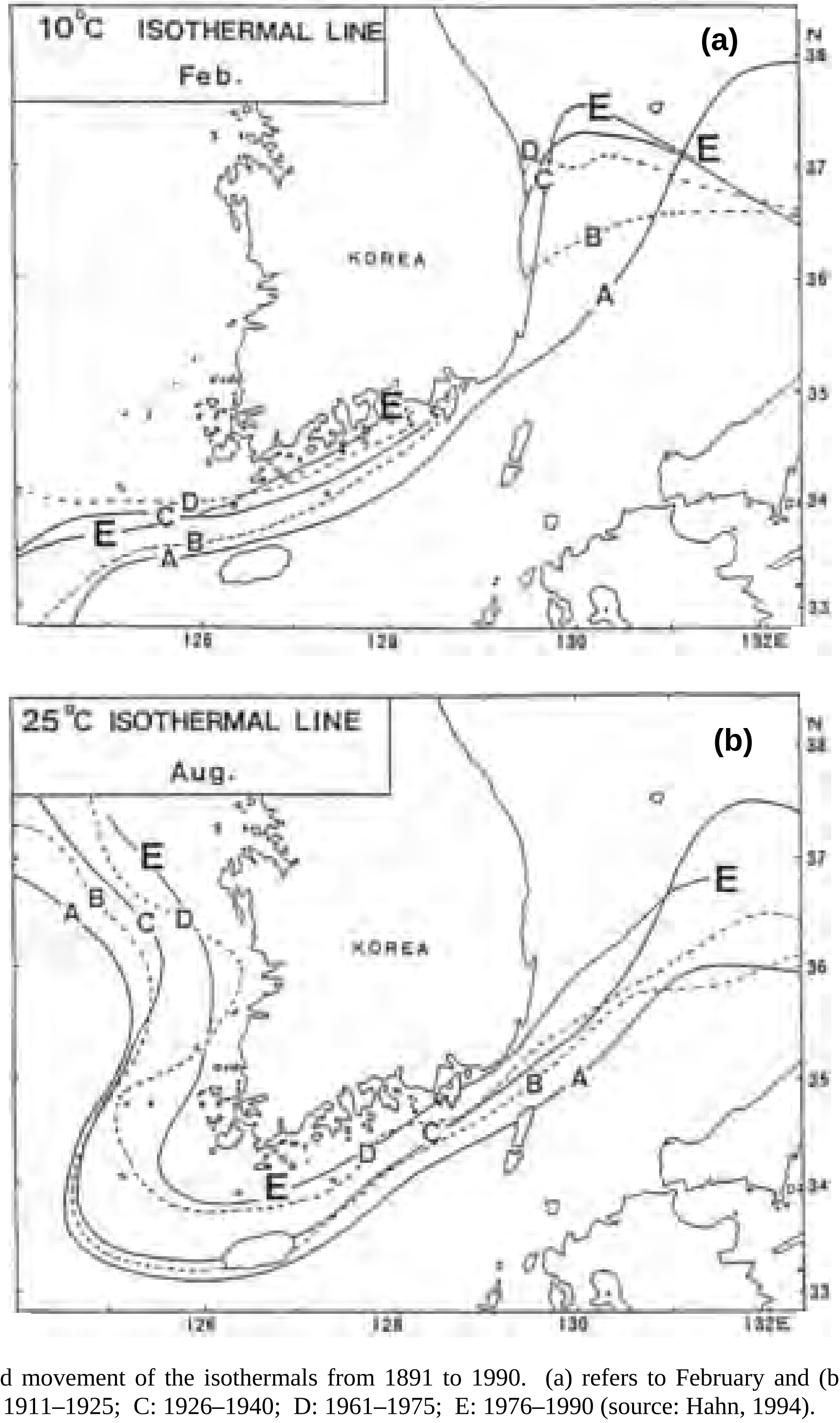


Fig. 43 Northward movement of the isothermals from 1891 to 1990. (a) refers to February and (b) refers to August. A: 1891–1910; B: 1911–1925; C: 1926–1940; D: 1961–1975; E: 1976–1990 (source: Hahn, 1994).

pattern: spawning in the coastal areas during the spring, feeding to the north during the summer, and overwintering after southward movement to the East China Sea.

Key Species in the Fishery

The fish species selected in this report are pollock, chum salmon, small yellow croaker, hairtail, anchovy, Japanese sardine, chub mackerel, jack mackerel, filefish, Pacific saury, skipjack tuna, and common squid. These are the key species in catch, accounting for more than 75% of the total catch since 1980 (Table 25). Most species have a wide range of distribution/migration around the Korean Peninsula. Unfortunately, the biology of these species has not been studied extensively.

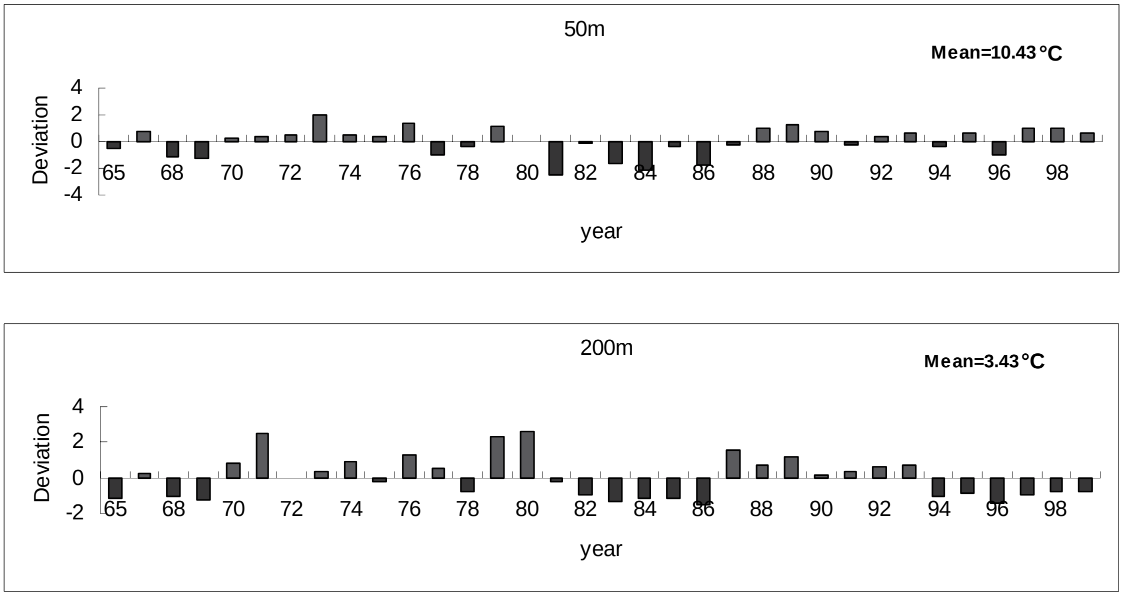


Fig. 44 Change in seawater temperature in April at 50 and 200 m depth in the East/Japan Sea.

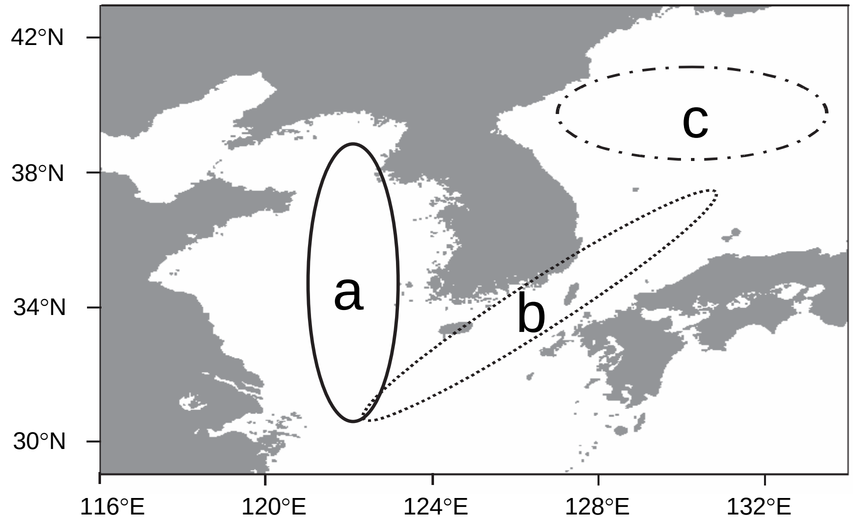


Fig. 45 Three categories of fish communities in Korean waters. (a) Demersal ecosystem in the Yellow Sea: small yellow croaker, and hairtail, (b) pelagic ecosystem in the East China Sea through the southern East/Japan Sea: mackerel, squid, and anchovy, and (c) demersal ecosystem in the East/Japan Sea: Pollock and Pacific cod.

Table 25 Catches (t) of major species in the Korean fisheries (FAO data).

	1980	1985	1990	1995	2000
Pollock	286,158	451,305	321,496	345,888	86,143
Chum salmon	128	2,353	666	1,455	28
Small yellow croaker	48,843	6,872	27,890	25,719	19,630
Hairtail	119,980	127,608	103,970	94,596	81,050
Japanese anchovy	169,657	143,512	168,101	230,679	201,192
Japanese sardine	38,282	107,776	132,924	13,539	2,207
Chub mackerel	62,690	68,479	97,227	200,481	145,908
Jack mackerel	565	16,343	17,429	12,269	19,510
Filefish	229,230	256,529	230,252	1,755	9
Pacific saury	12,395	4,393	23,103	37,865	44,340
Skipjack tuna	2,526	14,132	138,491	137,848	137,008
Common squid	48,490	42,879	75,293	200,897	226,309
Total	1,018,944	1,242,181	1,336,842	1,302,991	963,334

Walleye pollock (*Theragra chalcogramma*)

Biology

Walleye pollock mature at age 3 when their size reaches about 25 to 30 cm. They spawn in shallow water near the coast, and Won-San Bay in the Democratic People's Republic of Korea is as the largest spawning ground in the East/Japan Sea. The older and larger fish spawn first. The optimum water temperature of spawning pollock ranges from 2° to 5°C. The peak spawning season varies with regions: November to December in southern Korean Peninsula waters, December near Won-San Bay, and January to February off the northeastern Korean Peninsula (Gong and Zhang, 1983). Pollock are distributed along the coastal areas of the northern East/Japan Sea, from the southern to northern regions of the Korean Peninsula, Russia, and Japan. They reside in offshore areas, but move to the coastal areas for spawning. In general, pollock tend to move to the upper layer in the winter and to the deep layer in the summer when warm water masses are strong in the surface layer. Fecundity ranges from 250,000 to 400,000 eggs (Chyung, 1974). Pollock move southward from the Russian coast to the southern coastal areas of Korea in the spawning season.

Fishery

Korea has a long history of participation in pollock fisheries (Park, 1978). Modern fishing and catch statistics on pollock started in the early 20th century. Because pollock are a cold-water species, fishing activities were common traditionally in northern Korean Peninsula waters (*i.e.*, Democratic People's Republic of Korea), and this fishery was not popular in the southern part of the Korean Peninsula before the Korean War. However, catch statistics from the Democratic People's Republic of Korea have not been correctly reported since the 1940s. In the northern Korean Peninsula waters, pollock catches were high in the middle of 1980s, with a peak around 1.8 million t in 1983 (Kim and Kang, 1998). They decreased to 400,000–500,000 t in the 1990s, and unofficial records have recently indicated a very low catch in these waters.

Parts of the pollock population moved to the south along the coast, though the main group remained in northern Korean Peninsula waters. Annual catches increased from the early 1970s and peaked in 1981 at 165,000 t in the waters of the southern Korean Peninsula (Fig. 46). Since then, catches have declined continuously. One typical characteristic of the Korean pollock catch is the inclusion of immature juvenile pollock (called small pollock of ages 1 to 2 in Korean statistics). The proportion of immature pollock was higher than 90% in the late 1970s, decreasing continuously to 40% in 1987, and to 18% in 1988. In 1990, it increased to 63%, but decreased to 12% in 1997. For this species, there was no legal measure to protect juveniles, so that overfishing of juveniles might have influenced recruitment.

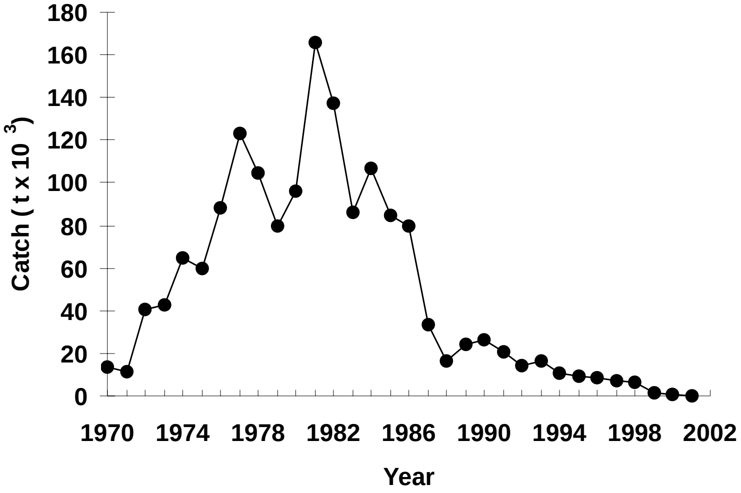


Fig. 46 Annual catches (t) of pollock in Korean waters from 1970 to 2002.

Climate and ocean effects

The majority of pollock reside in northern Korean Peninsula waters, but no fisheries or environmental data are available. The fishing areas in the 1990s (*i.e.*, warm seawater and low pollock biomass) were restricted to coastal areas, apparently because of the higher SST in the south. This contrasts with a broader fishing area in the late 1970s when SSTs were cooler. 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. There is a negative correlation between fish catch and seawater temperature at 50 to 100 m depth (Fig. 47). A negative anomaly in SST during the early 1980s was coincident with a positive anomaly of pollock catch, while warm water masses in the early 1970s and 1990s resulted in low pollock catches. Pollock catches are also significantly related to the Northeastern Pacific Pressure Index (Kang *et al.*, 2000).

Chum salmon (*Oncorhyncus keta*)

Biology

Five species of Pacific salmon, chum (*Oncorhynchus keta*), cherry (*O. masou*), pink (*O. gorbuscha*), silver (*O. kisutch*), and sockeye (*O. nerka*) are distributed in the Korean waters. However, the distributions of pink, silver, and sockeye salmon are limited to the northern Korean Peninsula. Chum salmon and cherry salmon are the only species released for salmon enhancement in Korea. Hatcheries were established in 1913 on the northern Korean Peninsula, and intensive enhancement activities resumed in the mid-1980s in Korea.

Adult chum salmon are distributed throughout the North Pacific Ocean, and return to their home stream when they sexually mature at age 3 or 4. They lay eggs in streams (or ripened eggs are removed in the hatcheries), and the eggs require 100 to 120 days for hatching in in fresh water of around 4°C. In the spring, hatched larvae with yolk become fry in hatcheries, and the fry enter (or are released) to the sea. They remain in estuaries or coastal areas for a while, then migrate northward along the coast during the summer. They stay in the ocean for 2 to 5 years until they return to their natal rivers to spawn. The main diet of chum salmon caught from the Subarctic Current and Alaskan Gyre areas consist of zooplankton, such as copepods, pteropods, amphipods, euphausiids, and jellyfish (Nakamura *et al.*, 2001).

Fishery

Chum salmon catches were very poor until the late 1980s. However, since 1990, catches from set net fisheries were included in these catch statistics so that an abrupt artificial increase in catches in 1990 was shown (Fig. 48). The proportion of catch by set net fisheries in total catch was about 70 to 80% for the 1990s and decreased to 50–70% in the 2000s. Salmon catches were seriously reduced from 553 t in 1997 to 51 t in 2000. Catches increased slightly in 2002 though they were still less than 200 t.

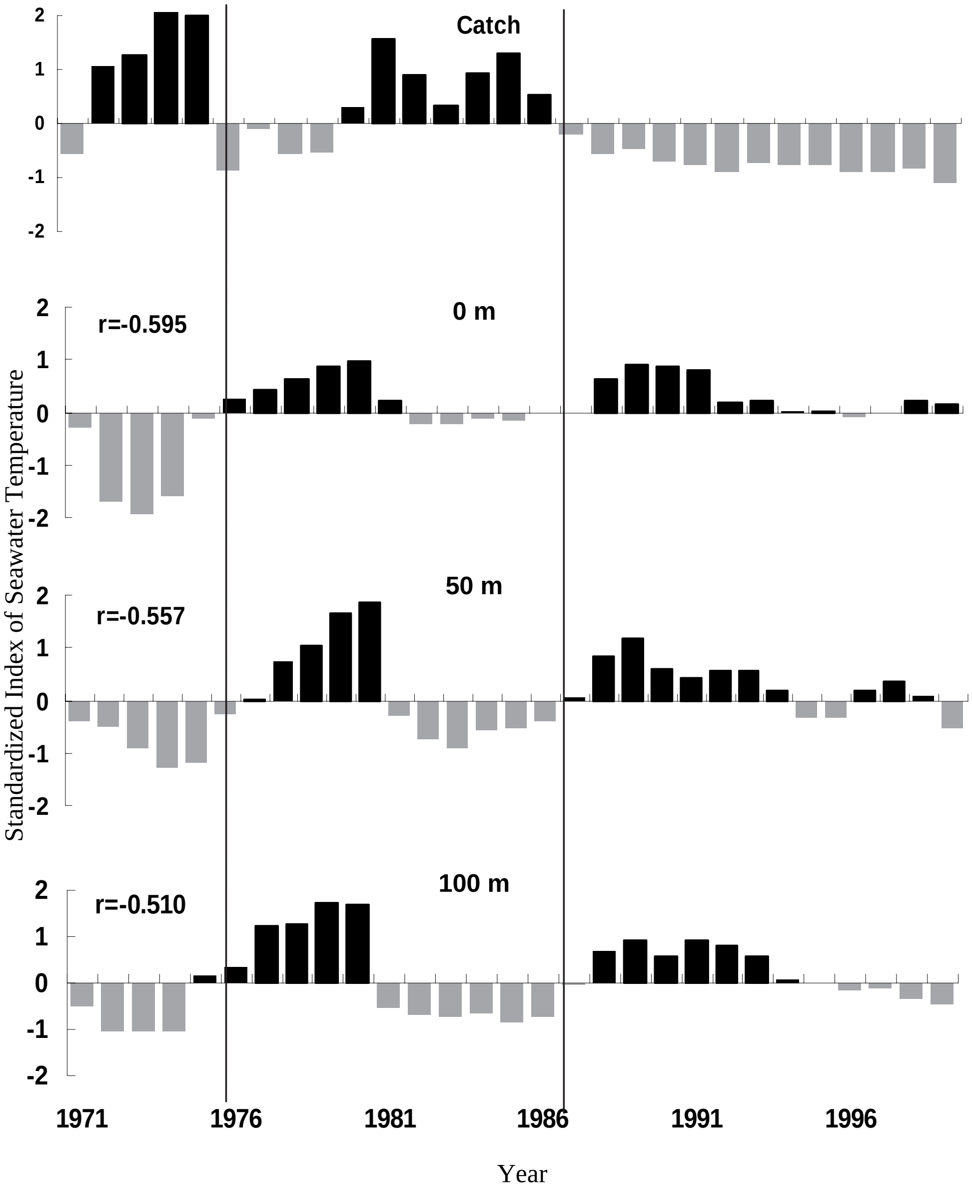


Fig. 47 The relationship between pollock catch and seawater temperature anomalies in Korean waters.

Climate and ocean effects

Because of the wide distribution of salmon throughout its whole life span, certain environmental conditions at specific areas influence salmon growth, migration route, and return rates. 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 less than 1% currently, which is relatively low compared to American and Japanese chum salmon. There was a negative correlation between return rates and SST in the coastal areas during the release time. The high temperatures in the spring of 1988–1990 and 1997–1998 appeared to be detrimental to the survival of released salmon fry and, in turn, resulted in the lower return rates of spawners in the 1991–1994 and 2000–2001 spawning periods, respectively (Fig. 49).

Bottom-up processes and seawater temperature seemed to influence the growth of chum salmon populations in Korea. Growth during their early life history in fresh water and river mouth areas was

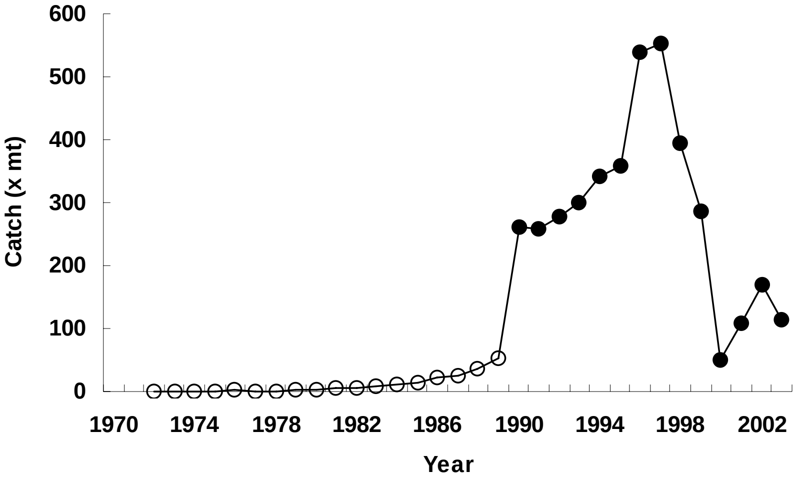


Fig. 48 Annual catches of chum salmon in Korean waters from 1991 to 2003. Open circles represent the catch amount in Korean rivers. Closed circles represent total catch amounts from rivers and set net fishery.

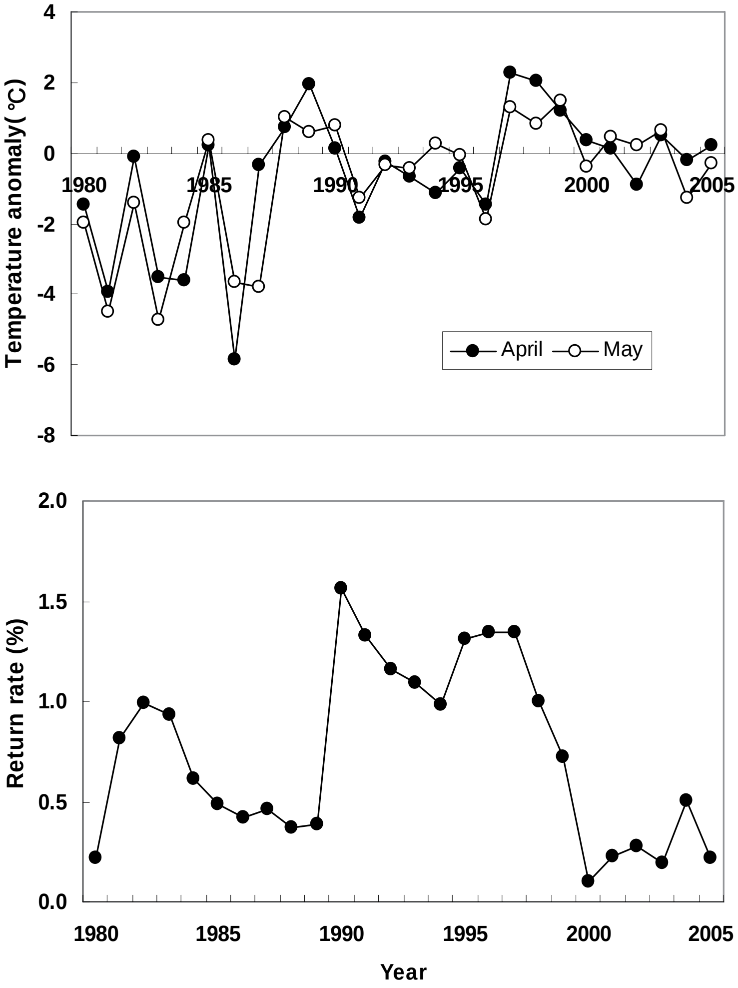


Fig. 49 Seawater temperature anomalies near salmon hatcheries and the return rate of Korean chum salmon. Note that the return rate before 1990 does not include salmon catch in coastal areas of Korea.

better in the early 1990s than in the 1980s. This phenomenon might be related to the increase in seawater temperature and zooplankton abundance off Korea (Fig. 50). On the other hand, salmon growth in the open ocean was better in the 1980s than in the early 1990s. The 1988/89 regime shift might have caused a change in environmental conditions, and ultimately, the growth of chum salmon in the open sea (Fig. 51). Interestingly, summer growth conditions at their first year of ocean life in coastal areas seemed to be stable during the 1980s and 1990s. In the southern Okhotsk Sea, there were relatively no big differences in seawater temperature and zooplankton biomass during the same time (figure not shown).

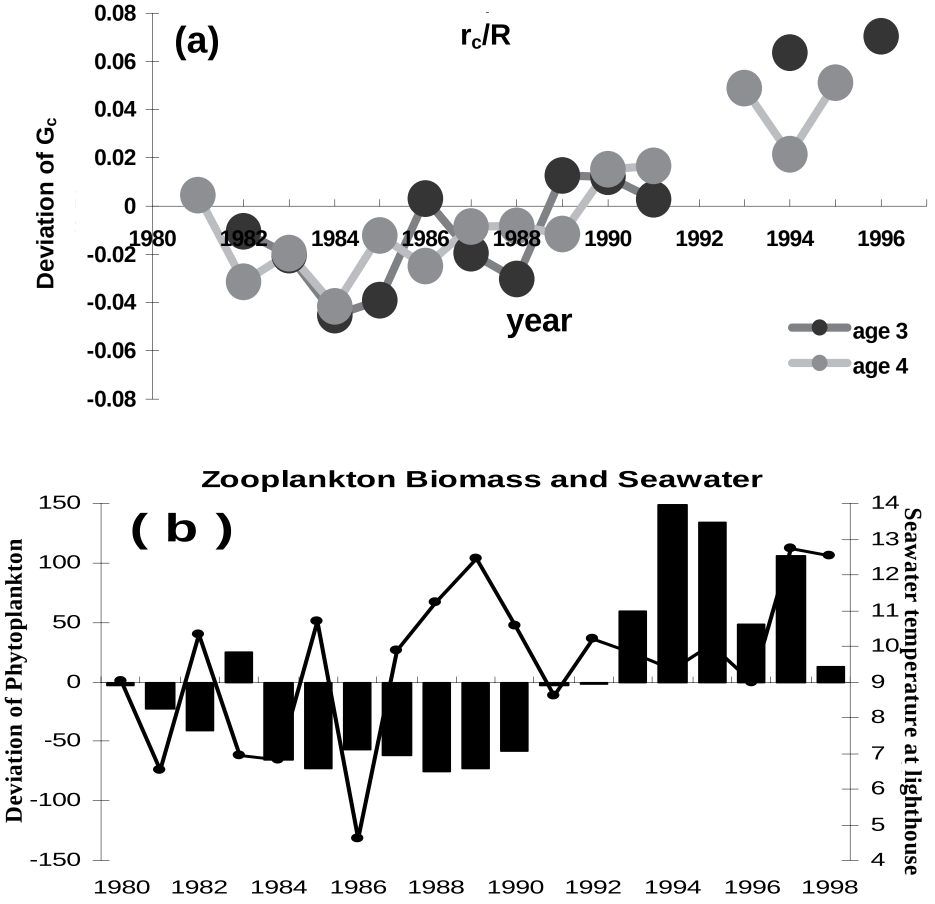


Fig. 50 (a) Deviations (G_c) from the average annual proportions of total scale growth of young chum salmon occurring in fresh water (r_c/R) where r_c is the distance from the focus to the scale check formed during the transition from the freshwater/coastal environment to ocean life, divided by R, the total distance from the focus to the perimeter of the scale and (b) deviations of zooplankton biomass (bars) and seawater temperature (line) in April off the east coast of Korea.

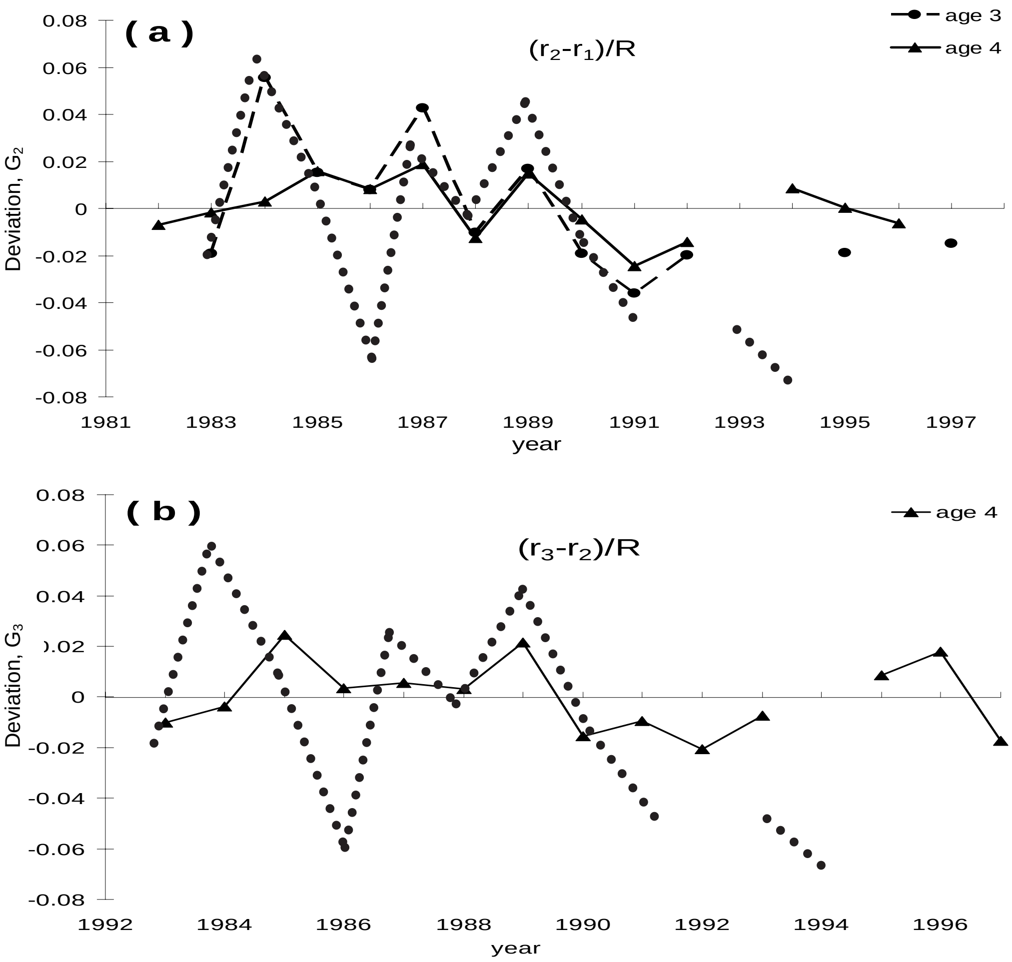


Fig. 51 Deviations (anomalies) from the average annual proportions of total scale growth occurring in (a) the second year (r_2/R) where r_2 is the length of scale added during the second year of growth at sea ($r_2 - r_1$) divided by R, the total distance from the focus to the perimeter of the scale. Similar in (b) for the third year of growth at sea. Year-to-year variation in the mean macro-zooplankton biomass (dotted line) in the eastern Bering Sea was superimposed (Sugimoto and Tadokoro, 1997). Growth information was derived from returning female salmon to their natal streams at age 3 and age 4 years from 1984 to 1998. The *x*-axis represents the year of growth.

Small yellow croaker (*Pseudosciaena polyactis*)

Biology

Small yellow croakers migrate to the East China Sea in the winter and return to the Yellow Sea to spawn in the spring. The spawning season is from April to June, with a peak in May in the eastern part of the Yellow Sea. The species used to mature at age 5 (NFRDI, 2005), but recently they seem to be maturing earlier. The majority of fish in the fishery are 1- or 2-year-olds, with a mean age of 1.6 years (Kim *et al.*, 1997).

Fishery

Small yellow croaker is an important commercial species off the west coast of the Korean Peninsula. Fishing fleets traditionally target spawning schools. However, recent heavy exploitation has resulted in limited spawning schools in the Yellow Sea. Since the 1980s, the main fishing activities have moved from the Yellow Sea to the East China Sea. Annual catches of small yellow croaker have fluctuated largely in the Yellow Sea and the East China Sea. From the early 1970s to the early 1980s, the annual catches were about 30,000 to 50,000 t, but decreased below 10,000 t after the mid-1980s (Fig. 52). Catches increased in the early 1990s, and have since continuously decreased. Recent catches were below 10,000 t. The annual catches per unit effort (CPUE) were higher in the 1970s, but lower after the 1980s (figure not shown).

Climate and ocean effects

Small yellow croaker is a demersal species in the Yellow Sea and the East China Sea, so that the survival of newly spawned eggs might be affected by temperature at depth. It was found that cold and variable temperatures, especially seawater temperature at 75 m depth in the Yellow Sea, during the early life history of yellow croaker resulted in poor yields or weak year classes in the following years (Kim *et al.*, 1997). The seasonal anomaly of mean temperature at 75 m depth with the seasonal anomaly of fish catch was positive and significant, with a time lag of 8 to 14 months (Fig. 53).

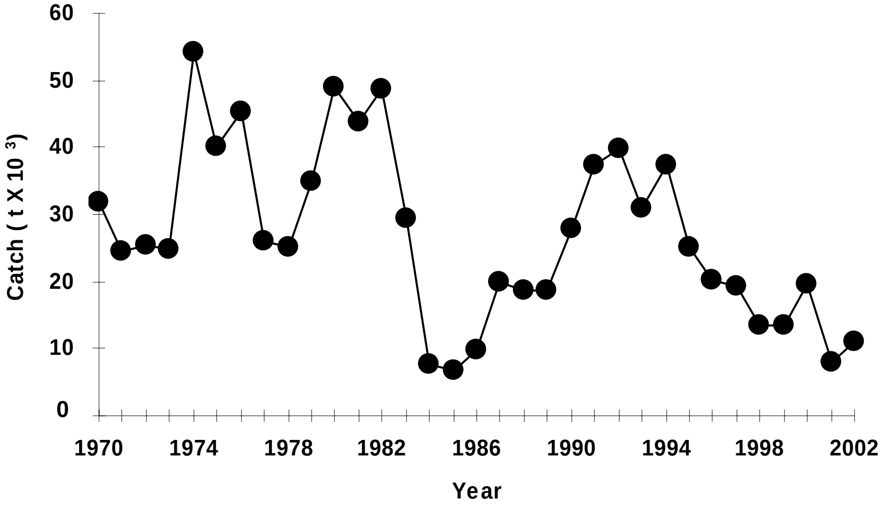


Fig. 52 Annual catches of small yellow croaker in the Yellow Sea and the East China Sea from 1970 to 2002.

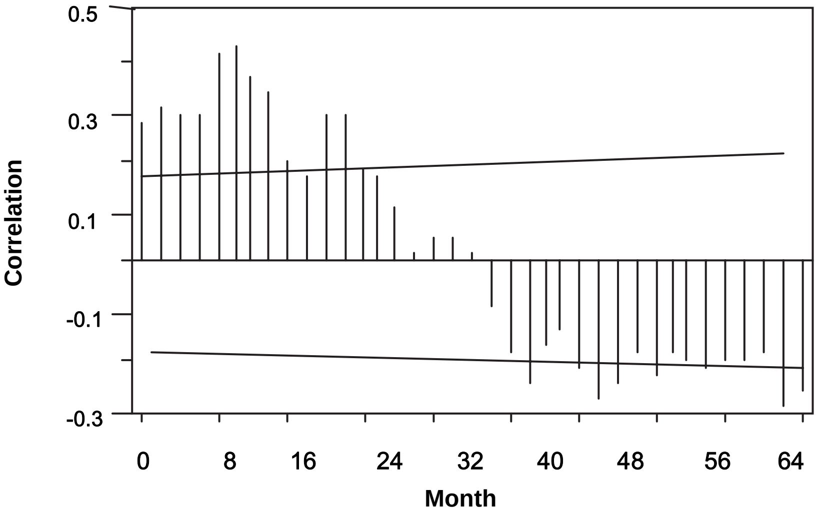


Fig. 53 Cross-correlation coefficient between seasonal anomalies of small yellow croaker catch and seawater temperature at 75 m depth.

Hairtail (*Trichiurus lepturus*)

Biology

Spawning occurs between June and October with a peak in August. Hairtail are multiple spawners that spawn two or three times in a single season. Fecundity ranges from 13,000–126,000 eggs (Kim *et al.*, 1998). Hairtail are carnivorous and consume mainly fish, crustaceans (such as copepods, euphausiids and shrimps), and chaetognaths. Their diet also includes small quantities of small squid. Hairtail have an ontogenetic progression in their feeding stages: an initial stage is planktivorous, in which they feed mainly on copepods, followed by a mixed feeding stage in which euphausiids, mysids, shrimps, chaetognaths and fish are the major food items. Anchovies are major prey of large hairtail (Huh, 1999).

Fishery

The annual catch of hairtail was relatively large, with over 100,000 t, caught from the mid-1970s to the mid-1980s. There was a decreasing trend beginning in the late 1980s that has continued to recent years (Fig. 54).

Hairtail are distributed in the southwestern waters off Jeju Island from January to March. The majority migrates northward along the west coast of the Korean Peninsula and reaches the central part of the Yellow Sea in July and August. The return migration southward begins in September and reaches the wintering area off Jeju Island by November. However, some groups of the stock also migrate northeast in March, and stay off the southern coast of the Korean Peninsula in May to June, and the southeastern waters in September. In September, these groups move back to the wintering ground off Jeju Island (Park *et al.*, 2002).

Climate and ocean effects

When the bottom water of western Jeju Island was above 14°C in the summer, the catch was large. In contrast, the catch was poor when the temperature was below 13°C. Therefore, the temperature of the bottom layer can be used as an index for forecasting the catch of hairtail (Kim and Rho, 1998).

Anchovy (*Engraulis japonicus*)

Biology

Anchovy occur primarily in the warm water area of the Korea Strait and the southern area of the Yellow Sea during the winter, and migrate shoreward to the southern coast of Korea to spawn from April to August. Spawning occurs at a fork length of 9 to 12 cm during May through July, whereas adults above 12 cm spawn from March to September. Anchovy are serial spawners, and fecundity ranges from about 15,000 to 23,000 eggs, with specific batch fecundity of 438 ± 146 (Kim and Kang, 1992).

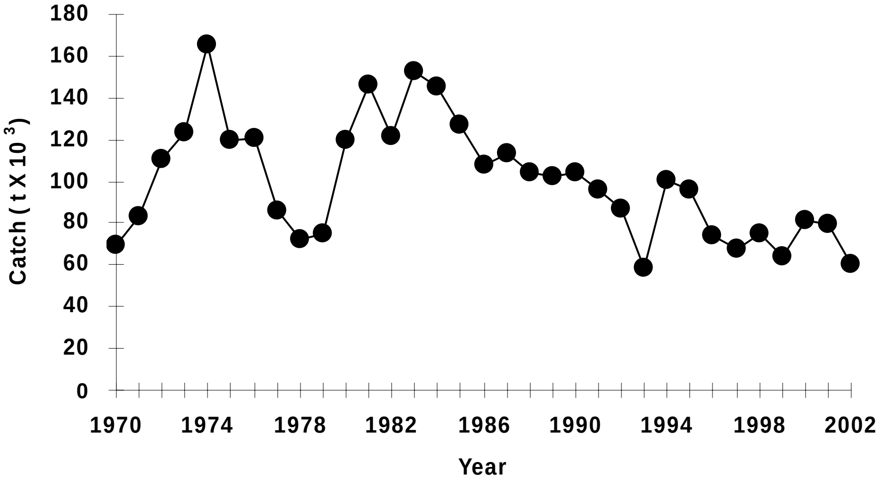


Fig. 54 Annual catches (t) of hairtail in the Korean waters from 1970 to 2002.

Fishery

The fishing grounds for anchovy are in the southern coastal waters within 35 to 55 km off the Korean Peninsula. Annual catches of anchovy increased from 1970 and remained around 150,000 to 200,000 t from 1975 to 1993 (Fig. 55). The catch increased to about 240,000 t in recent years. However, the CPUE was remarkably low after the peak in 1975. The fishery targets juveniles with anchovy drag and set nets, and adults with drift gill nets.

Climate and ocean effects

Annual variation in oceanographic conditions affects the adult migration route and the distribution of eggs and larvae. The resulting changes in distribution affect the locations and time of fishing. Seasonal and long-term trends of the size of yolk-sac larvae (Kim, 1992), embryonic mortality, egg production, and spawning stock biomass of anchovy are related to spring warming, summer cooling, and zooplankton biomass (Kim and Lo, 2001). Seawater temperature data from 1983 to 1994 showed an increasing trend in April and a decreasing one in June (Fig. 56). The trend in egg mortality, however, was opposite: daily mortality decreased in the spring (May) and increased in the summer (July) during 1983 to 1994 (Table 26).

Anchovy eggs and larvae are produced in June and August. They are distributed in warm, saline water in June, and are carried offshore by currents in August. It is likely that the distribution of anchovy eggs and larvae in June are significantly correlated with oceanic conditions in the eastern waters of Korea (Kim, 1992). In summer (August), when the Tsushima Warm Current is strong near the coast, warm waters, such as warm streamers from the Tsushima Warm Current, intrude into the coastal area, and cyclonic circulations are formed. Anchovy eggs and larvae are transported to the coastal area by these eddies. Larval survival and growth have increased because of high primary production in these circulations (Choo and Kim, 1998).

Anchovy catch is highly correlated with chlorophyll (Chl-*a*) concentrations in June and August, and with large zooplankton such as chaetognaths, euphausiids, and amphipods during autumn through spring (Kim and Kang, 2000; Table 27).

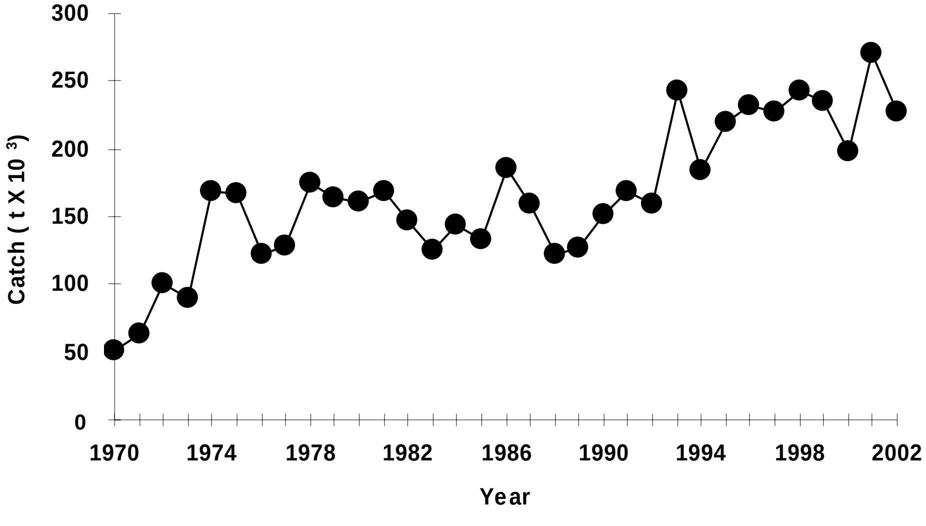


Fig. 55 Annual catches of anchovy in the Yellow Sea and the East China Sea from 1970 to 2002.

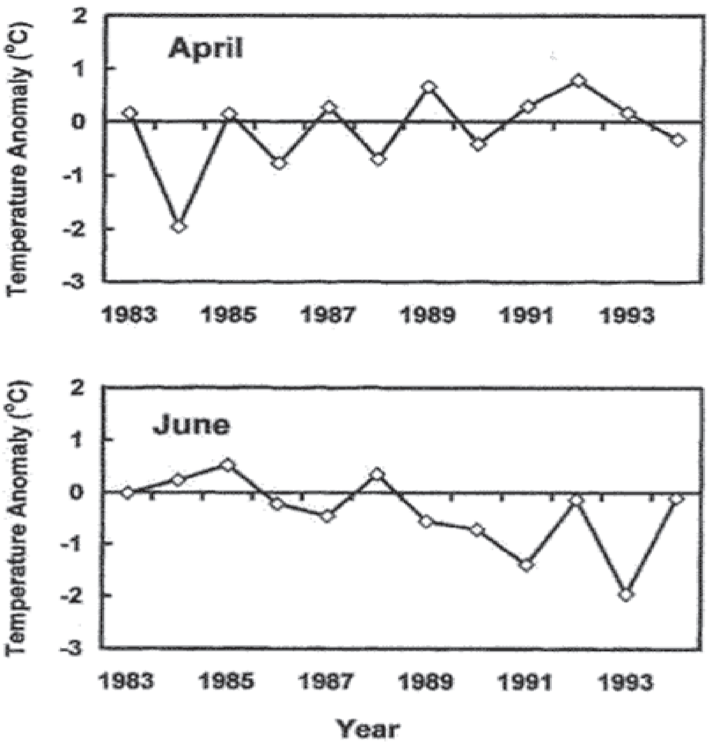


Fig. 56 Yearly variation of seawater temperature anomaly at 10 m depth in the southern waters of Korea from 1983 to 1994. Mean temperatures in April and June are 14.28 ° and 19.78 °C, respectively.

Table 26 Estimates and coefficients of variation (CVs) of daily egg production and mortality rate of the anchovy embryonic stage in spring and summer for three periods: 1983–1986, 1987–1989 and 1990–1994 (Kim and Lo, 2001).

	Number of samples		Egg production		Mortality at embryo stage	
Season and period	**Total**	**Positive station**	**Production (m^{-2})**	**CV**	**Mortality (day^{-1})**	**CV**
Mid 1980s (1983–1986)						
Spring (May)	171	137 (80%)	385.62	0.38	1.23	0.44
Summer (July)	140	111 (79%)	1356.19	0.39	0.78	0.81
Late 1980s (1987–1989)						
Spring (May)	105	68 (65%)	144.07	0.41	0.41	0.77
Summer (July)	106	88 (65%)	531.73	0.45	0.87	0.84
Early 1990s (1990–1994)						
Spring (May)	93	53 (57%)	174.29	0.23	0.33	0.53
Summer (July)	63	47 (75%)	1163.94	0.33	1.69	0.27

Table 27 Selected correlation coefficients, which are statistically significant for fish catch versus their biotic and abiotic environmental factors.

Variable	**Anchovy** ***Engraulis japonica***	**Mackerel** ***Scomber japonicus***	**Sardine** ***Sardinops melanosticta***
Anchovy	1.0	0.790**	0.453*
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

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).

Japanese sardine (*Sardinops melanostictus*)

Biology

Sardines spawn off the southern waters of the Korean Peninsula from December through June with a peak spawning period in February to April. They migrate north in the summer to feed around 45°N along the eastern coast of the Peninsula and in November, move south to the southern coast. They recruit to the fishery at age 1 and mature at age 3.

Fishery

Japanese sardine catches show two high peaks in the northwestern Pacific in the 20th century: the late 1920s to the early 1940s and the mid-1970s to the early 1990s. In Korean waters, a peak harvest of 1,388,000 t was recorded in 1937. Catches declined over a period of 25 years from the mid-1940s to the 1960s. Sardine catches increased rapidly from about 38,000 t in 1980 to 200,000 t in 1987. However, they declined again from the late 1980s. Annual catches of sardines fell below 2,000 t from 2000 to 2002 (Fig. 57).

Climate and ocean effects

The intensity of the Kuroshio Current has increased since 1976. As a result the intensity and frequency of spring blooms has decreased in the East/Japan Sea and the intensity of autumn blooms has increased. Sardines are resident in the East/Japan Sea from June to November. Thus an autumn bloom is more advantageous to them than a spring bloom, and this may account for the dramatic increase in the sardine stock after 1976 (Zhang *et al.*, 2000). Sardine catch is positively correlated with Chl-*a* concentrations in April and negatively correlated with chaetognaths in April and euphausiids in June (Kim and Kang, 2000; Table 27).

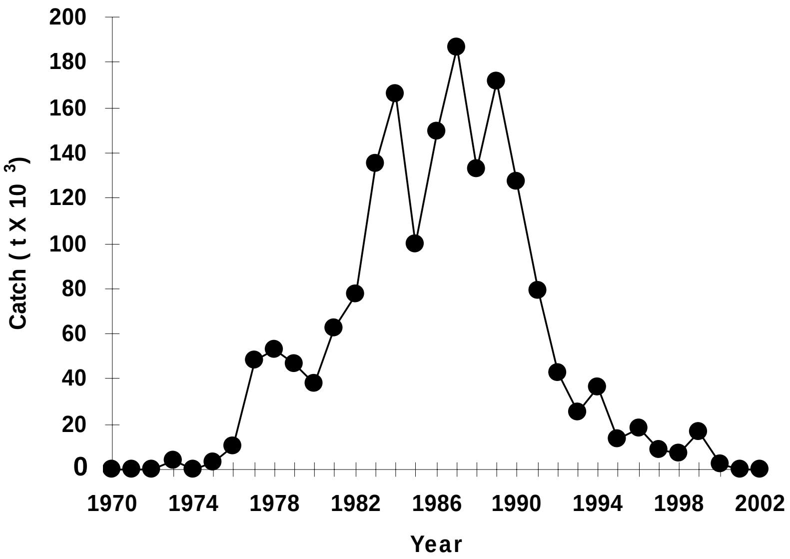


Fig. 57 Annual catches of Japanese sardine in the Yellow Sea and the East China Sea from 1970 to 2002.

The abundance and geographical coverage of sardine eggs and larvae were high in the 1980s when spawning biomasses were high in the mid-1980s, and vice versa in the late 1970s and the early 1990s. Decadal-scale changes in seawater temperature at 50 m depth during spring indicated warm temperatures in late 1970s followed by cool waters during the early to mid-1980s, and warm again since the late 1980s. Feeding and spawning areas, based on fisheries information, also exhibited the same pattern of extension and contraction as seen in ichthyoplankton surveys. The annual gonado-somatic index in spawning seasons (February–April) and the size of sardines were reduced during the high abundance period. It is possible that density-dependent processes affect the life-history parameters of the sardine populations in Korean waters (Kim *et al.*, 2006).

Chub mackerel (*Scomber japonicus*)

Biology

Chub mackerel that migrate throughout warm water are widely distributed and caught in the western, southern, and southeastern seas around the Korean Peninsula, in the East China Sea, and around Japan. This species is distributed on the continental shelf from the surface to 300 m depth in the Yellow Sea and the East China Sea (Fig. 58). Chub mackerel spawn from February to May when the water temperature ranges from 15° to 23°C. They migrate to the wintering grounds between Jeju Island and Tsushima Island in the East China Sea from December to February. The fecundity of chub mackerel ranges from 112,000 to 570,000 eggs, and the fork length of 50% mature females is 28.7 cm (Choi, 2003).

The mean length of chub mackerel has tended to decrease since the 1970s, and the portion of small mackerel has increased (Fig. 59). The fork length was about 32 cm in the early 1970s, but it has continuously decreased, and the mean fork length in 2002 was 29.2 cm. Some biological parameters, such as natural mortality, maturity length, and recruitment age have been estimated (Table 28).

Fishery

About 70 to 80% of the worldwide total catch of chub mackerel occurs in the northwestern Pacific Ocean by countries including Korea, Japan, and China (FAO, 2000). Korean annual catches were below 100,000 t until the mid-1980s, and increased to 150,000 t in 1988 and 1989 (Fig. 60). The annual catch was just 100,000 t in the early 1990s. However, it started to increase to over 150,000 t from the mid-1990s and reached its highest level of 415,000 t in 1996. Currently the catch is about 170,000 t. This species is usually caught by large purse seines, drift gill nets, and set nets in Korean waters. About 90% of the total chub mackerel catches are from the large purse seine fishery, mainly in the East China Sea and in the western and southeastern seas of Korea.

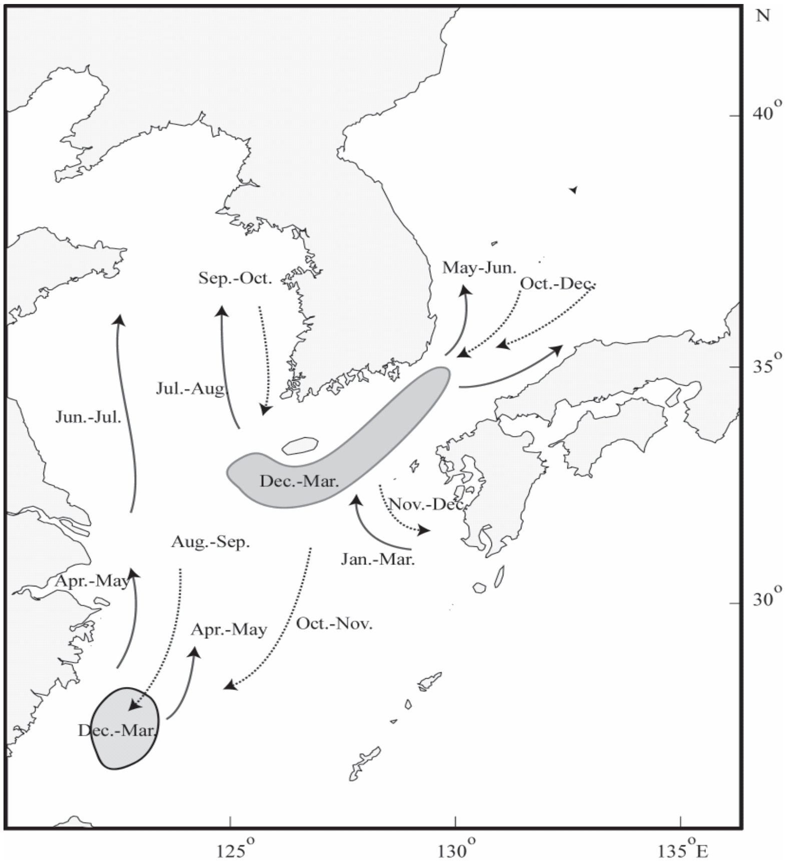


Fig. 58 Seasonal migration route of chub mackerel near the Korean Peninsula.

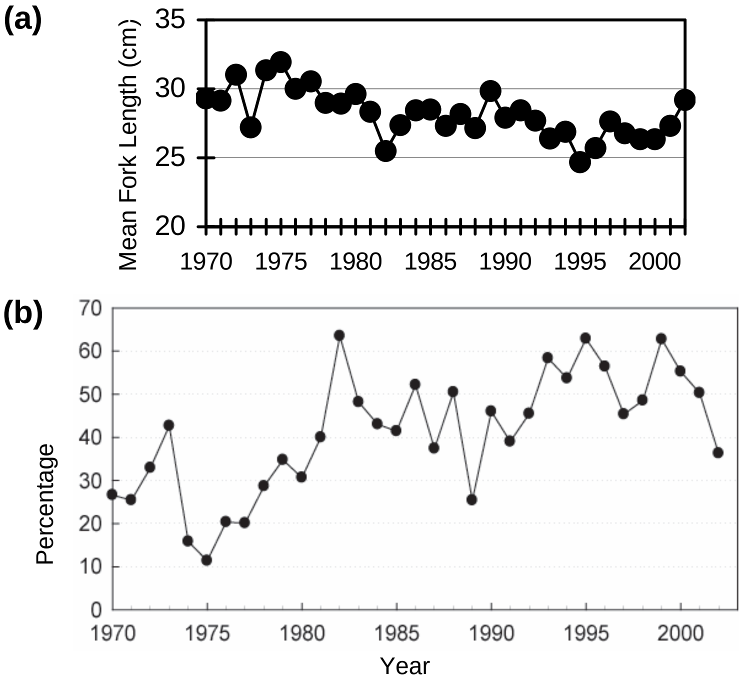


Fig. 59 (a) Long-term variation of mean fork length of captured mackerel, and (b) percentage of fish smaller than the 50% maturity length of the total mackerel catch from Korean waters.

Table 28 Estimated biological parameters of chub mackerel.

Parameters	Estimates	Addition
Natural mortality	0.6 year^{-1}	
Maturity length (50%)	24.0 cm	fork length
Recruitment age	0.5 year	
Mean length (2002)	29.2 cm	fork length
Mean age (2002)	2 years	

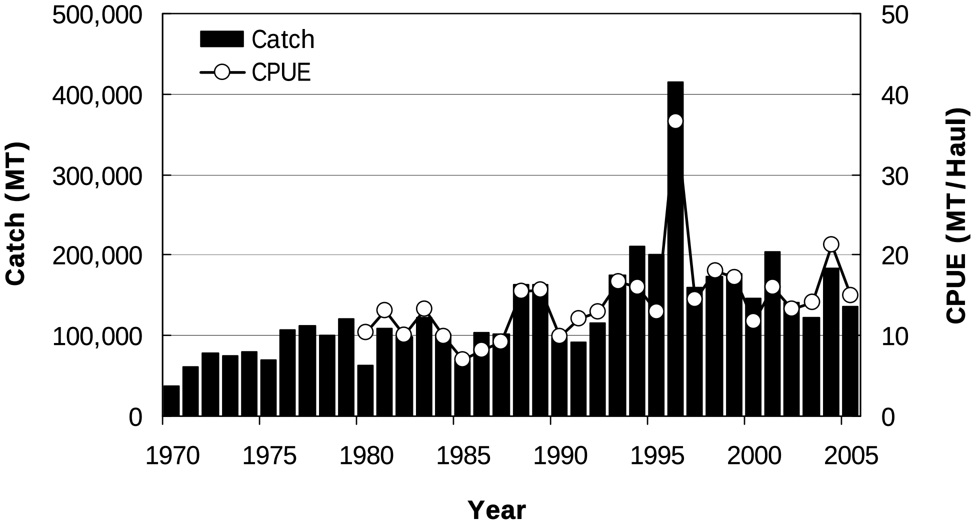


Fig. 60 Trend in annual catches and catch per unit effort (CPUE) of chub mackerel in Korean commercial fisheries in Korean waters from 1970 to 2006.

Climate and ocean effects

A significant change in recruitment was found in correlation with salinity ($r = 0.454$, $P < 0.05$), with zooplankton biomass ($r = 0.692$, $P < 0.01$), and with copepod biomass ($r = 0.815$, $P < 0.01$) (Choi *et al.*, 2000). Also, chub mackerel catches were highly correlated with SST in December, Chl-*a* in June, and large zooplankton in the fall and early winter (Table 27).

Chub mackerel share 35.7% of their habitat with both jack mackerel and Pacific sardine, and 28.6% with jack mackerel or 3.1% with Pacific sardine in Korean waters (Zhang and Gong, 2005). The 1988 climatic regime shift affected the habitat of chub mackerel by widening and moving it to the west of 128°E (Fig. 61). After 1988, the distributional overlap of chub mackerel and jack mackerel decreased. These shifts in the habitats of jack mackerel and chub mackerel resulted in Japanese sardines occupying a habitat area separated from the shared mackerel distributions. Replacement in biomass between chub mackerel and Japanese sardine stocks resulted from the competition of prey and space among major small pelagics in Korean waters (Zhang *et al.*, 2000).

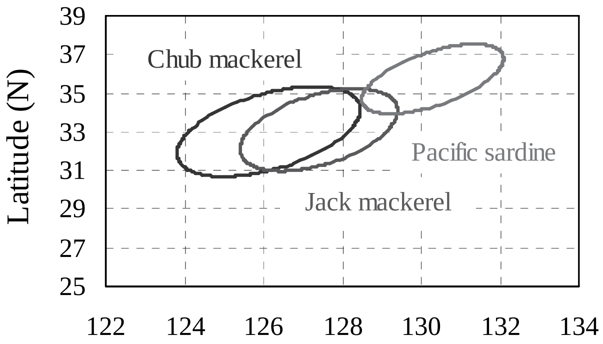
Jack mackerel (*Trachurus japonicus*)

Biology

This species migrates to the northern East China Sea during January–March and to the spawning grounds near the western Kyushu Islands and areas between Jeju Island and Tsushima Island during April–May (Lee, 1970; Nakashima, 1982). Jack mackerel spawn when water temperatures range from 16° to 22°C. In the East China Sea, the main distribution area of larvae is the Kuroshio frontal region along the continental margin in the winter and spring. The species usually feeds on zooplankton, including larvae of anchovy and big-eye sardine (*Etrumeus teres*). As the fish grow older, they move to deeper water and feed on larger prey, such as amphipods and mysids, but usually not copepods (Cha, 1991).

There is evidence that the recruitment of jack mackerel is determined by the degree that eggs and larvae are affected by environmental factors. These factors are seawater temperature, salinity, volume transport of the Kuroshio Current, and zooplankton biomass in Korean waters (Zhang and Lee, 2001). Significant increases in salinity in April, volume transport of the Kuroshio Current, and zooplankton biomass were observed and were significantly correlated with increased recruitment of jack mackerel in the following year (Table 29).

(a) 1980–1988



(b) 1989–1998

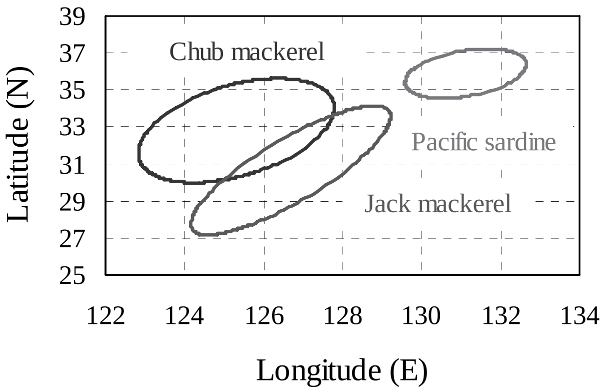


Fig. 61 Joint confidence regions in the habitat of major small pelagics in Korean waters during the periods of (a) pre- and (b) post-1988 climatic regime shift (Zhang *et al.*, 2004). Ellipses of the fishing block weighted by catch per unit effort (CPUE) were calculated for each species in the Korean large purse seine fishery.

Fishery

Jack mackerel (*i.e.*, horse mackerel) are widely distributed and caught in the Yellow Sea, the East China Sea, and the southern East/Japan Sea (Kim, 1970). They are usually caught by large purse seines, bottom trawls, and drift gill nets in Korean waters. About 80% of the total catches are from the large purse seine fishery, mostly in the East China Sea waters of Korea. Annual catches reached their highest level of 48,000 t in 1956, and then declined below 10,000 t in the late 1960s. In the early 1980s, the annual catch increased and has been about 23,000 t in recent years (Fig. 62). Over the past 70 years, the pattern of catch has been characterized by a cyclic behavior with a relatively low frequency of 30 years and a high coefficient of variation (CV) of 0.79.

Climate and ocean effects

The volume transport of the Kuroshio increased after 1977. The salty Kuroshio Warm Current intensified the Tsushima Warm Current connected with the Kuroshio in the inshore waters of southern Korea. Warm, saline waters had a positive correlation with the density of jack mackerel (Cho, 1981). Therefore, the increase in salinity of the East China Sea may have triggered the increases in the recruitment and biomass of jack mackerel in the early 1980s, resulting in increased catches.

The effects of the early 1980s environmental shift are hypothesized to have affected the productivity of the jack mackerel population (Fig. 63). As the volume transport of the salty Tsushima Warm Current increased, resulting in higher salinity in the East China Sea, spawning grounds for jack mackerel became more ideal. Consequently, high concentrations of the spawning stock were observed in this area. As the intensity of the Tsushima Warm Current increased, the variation of zooplankton biomass in the East China Sea waters of Korea was expected to correspond to the variation of stratification of ocean structure. Since the thermocline in the East China Sea is formed at 30 to 50 m depth, and the water is relatively shallow (75 to 150 m; NFRDI, 2005) where photosynthesis can be active in all seasons, the increase in zooplankton biomass may not have been directly related to the primary production in the early 1980s in the East China Sea waters of Korea. The increase of recruitment and biomass in the plankton-feeding jack mackerel stock after the early 1980s can be attributed to the aggregation of the spawning stock and the increase of prey in the East China Sea (Zhang and Lee, 2001).

Jack mackerel share 63.4% of their habitat with chub mackerel in Korean waters (Zhang and Lee, 2001). Jack mackerel share 36.6% of their habitat with both chub mackerel and Japanese sardine, and further, were not found to co-exist with Japanese sardine exclusively during the period from 1980 to 1998 (Fig. 61). The 1988 climatic regime shift affected the habitat of jack mackerel by shifting it southward to 27°N. After 1988, the distributional overlap of jack mackerel and chub mackerel decreased. These shifts in the habitats of jack mackerel and chub mackerel resulted in Pacific sardine occupying a habitat area separated from the shared mackerel distributions (Zhang *et al.*, 2004).

Table 29 Correlation coefficient matrix between the recruitment of jack mackerel and environmental factors (Zhang and Lee, 2001).

	Recruitment	**Temperature**	**Salinity**	**Volume transport**	**Zooplankton biomass**
Recruitment	1.000	–	–	–	–
Temperature	0.043	1.000	–	–	–
Salinity	0.529**	0.153	1.000	–	–
Volume transport	0.487**	–0.264	0.230	1.000	–
Zooplankton biomass	0.547**	–0.288	0.248	0.399*	1.000

** $P < 0.01$, * $P < 0.05$

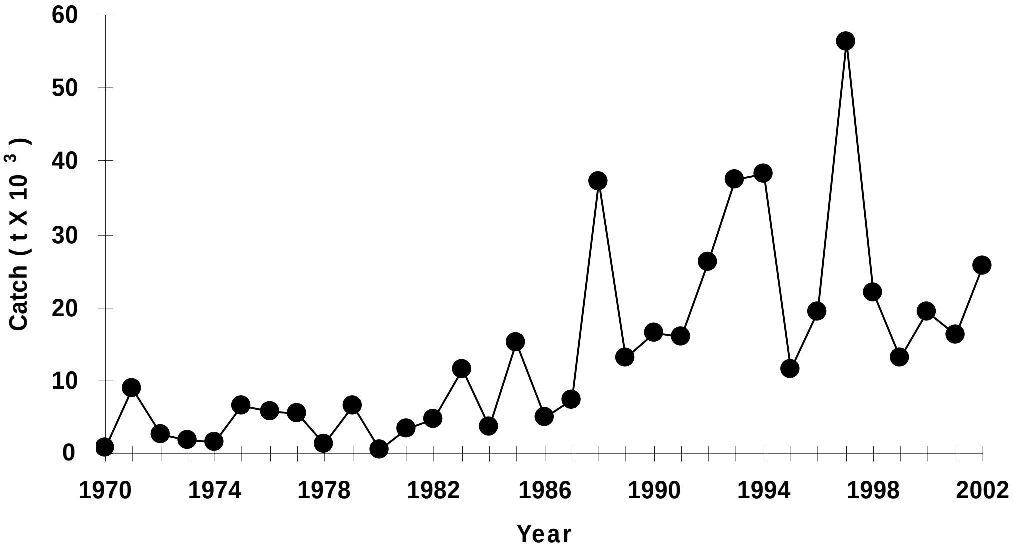


Fig. 62 Annual catches (t) of jack mackerel in Korean waters from 1960 to 2002.

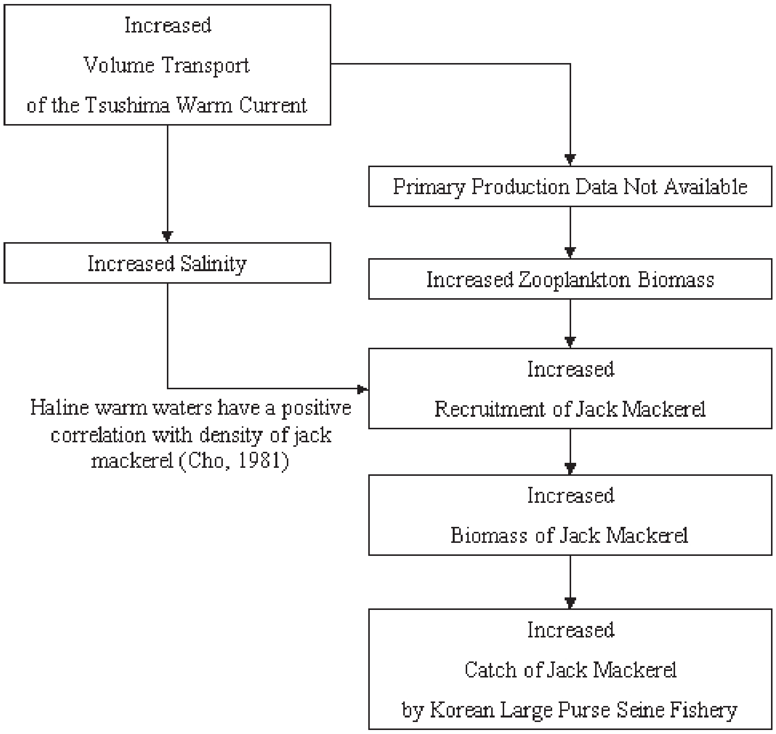


Fig. 63 Diagram showing the effects of the early 1980s climate regime shift on the jack mackerel population, based on the bottom-up hypothesis (Zhang and Lee, 2001).

Filefish (*Thamnaconus modestus*)

Biology

Filefish are a subtropical species that spend the winters in the East China Sea. They begin to migrate within the warm current in April, moving to the East/Japan Sea and the Yellow Sea. The northward migration to the East/Japan Sea along the Korean coastline begins in May, and some schools reach the northern Korean Peninsula coastal areas where they spend the summer. Eggs and larvae are advected by currents so that their distributions extend to the northern part of the East/Japan Sea. Another group that migrates to the Yellow Sea occupies the entire Yellow Sea in June, migrating southward beginning in October. Filefish are distributed from 5 to 200 m depth at seawater temperatures of 10° to 28°C. Spawning is from April to June. The total length at 50% maturity is 21 cm, and fecundity ranges from 210,000 to 1,460,000 eggs. The longevity of filefish is estimated to be 8 years, which corresponds to a total length of about 30 cm.

Fishery

Annual catches of filefish in Korean waters increased from 80,000 t in 1975, to about 230,000 t in 1979, and then declined slightly. After the mid-1980s catches increased sharply and peaked at 330,000 t in 1986. Catches fluctuated from the late 1980s to 1990, and dropped to 70,000 t in 1991, where they have remained at a very low level (Fig. 64).

Climate and ocean effects

Filefish productivity increased after 1976 when the warm currents became stronger (Fig. 65). There were some indications of climate regime shifts occurring in 1976 and around 1987 to 1989 in Korean waters. The indicators of these shifts were the patterns of seawater temperature, precipitation, volume transport of the Kuroshio, and mixed layer depth. Seawater temperature in the East/Japan Sea increased significantly in 1976 and 1987. In addition, precipitation and mixed layer depth in the East/Japan Sea, and the volume transport of the Kuroshio increased in 1976 and 1977. The increased volume transport of the Kuroshio in the East China Sea resulted in a strong influx of the Tsushima Warm Current into the Korea Strait and the East/Japan Sea.

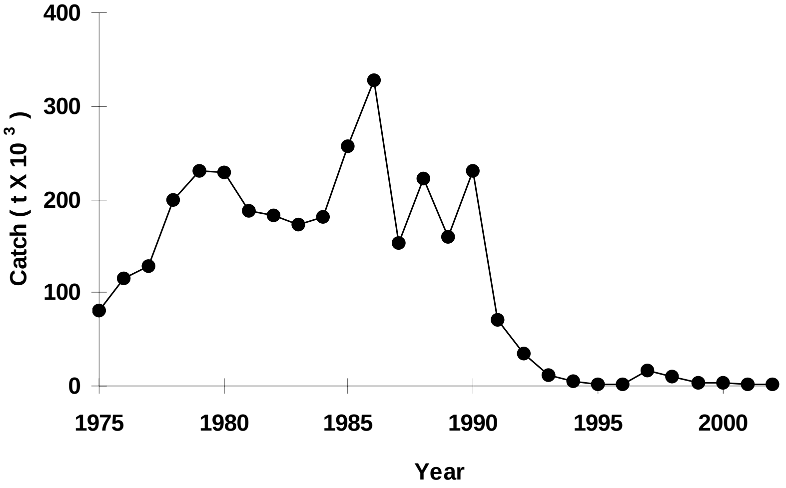


Fig. 64 Annual catches (t) of filefish in Korean waters from 1975 to 2002.

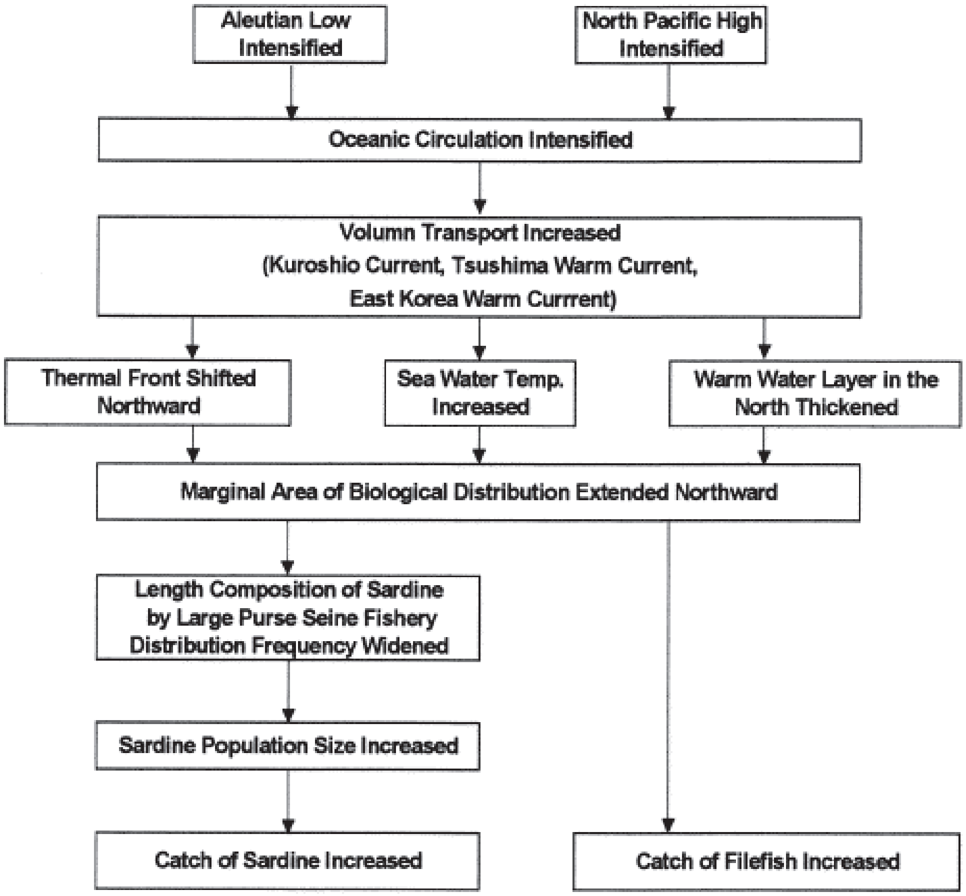


Fig. 65 Diagram showing the effects of the 1976 climate-driven regime shift on the filefish population in Korean waters (Zhang *et al.*, 2000).

Pacific saury (*Cololabis saira*)

Biology

The distribution of Pacific saury is determined by seawater temperature and salinity. They are not distributed in the western East China Sea and Yellow Sea, where salinity is low, but mainly reside in the East/Japan Sea and around Hokkaido. The migration area of Pacific saury has been limited to within the Tsushima Warm Current system. The stock that spends the winter near western Kyushu (January–March) moves to Ulleung Island in April to June. The southward migration of Pacific saury begins in September and reaches Tsushima Island in November to December.

Pacific saury are distributed from the surface to 30 m depth at seawater temperatures of 7° to 24°C. They spawn twice a year, in the spring and in autumn. The fork lengths at 50% maturity of the spawning groups in the spring and autumn are 22 and 30 cm, respectively, and the spawning periods are April to July and October to November, respectively. Fecundity ranges from 20,000 to 85,000 eggs. The longevity of Pacific saury is estimated to be 3 years, which corresponds to a length of about 35 cm.

Fishery

Pacific saury are caught mainly by stick-held dip nets and drift gill nets in Korean waters. Annual catches have fluctuated during the last four decades. The annual average catch was 25,000 t in the 1960s and early 1970s, but it started to decline sharply from 1976, dropping to about 2,000 t in 1984. Catches reached a minimum level of 500 t in 1992. They increased after the mid-1990s, and have fluctuated between 5,000 and 20,000 t in recent years (Fig. 66).

Climate and ocean effects

The increased volume transport of the Kuroshio in the East China Sea resulted in a strong influx of the Tsushima Warm Current into the Korea Strait and the East/Japan Sea that followed along into the North Pacific Current during the climate-driven regime shift in the mid-1970s and 1980s. Heavy rain, higher sea surface temperatures, unusual northward shifting of the polar front, and increased thickness of the warm water layer in the north resulted in a northward shifting of the overwintering ground of Pacific saury and an earlier-than-normal migration of the species to the spawning and feeding areas south and north of the polar front in the spring (Fig. 67).

The area of a stable thermocline in the coastal zone was reduced because of unusual westward and northward shifting of the polar front, which resulted in the reduction of primary production. The critical depth barely exceeded the deeper-than-normal mixed layer depth in the winter and early spring in the spawning and feeding grounds of Pacific saury during the early phase of the regime shift (1975–1977). Therefore, the delayed onset of the spring bloom of plankton (prey) and the earlier-than-normal arrival of spawning groups of Pacific saury resulted in the mismatch of prey and predator (larvae and

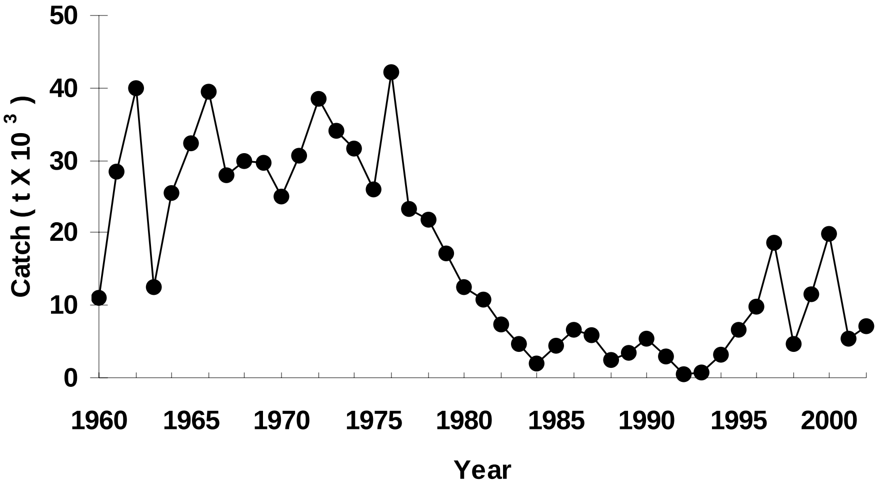


Fig. 66 Annual catches (t) of Pacific saury in Korean waters from 1960 to 2002.

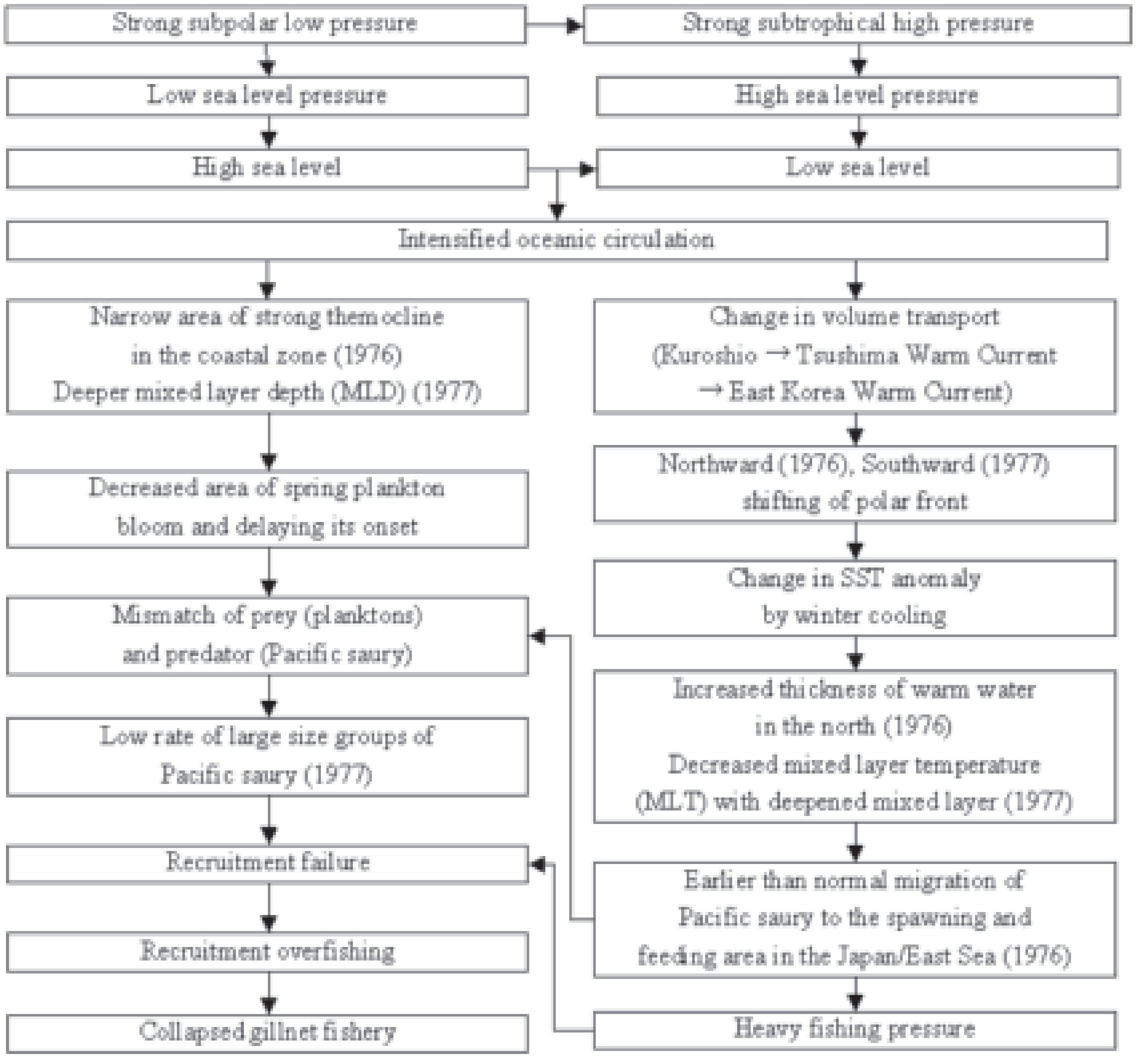


Fig. 67 Diagram showing the effect of the 1976 climate-driven regime shift on Pacific saury in the East/Japan Sea in the mid-1970s (Zhang and Gong, 2005).

adult) in the spawning and feeding grounds. The dramatic decrease in the ratio of the large size group of Pacific saury and abrupt drop of catches and abundance may have been caused by heavy fishing under the destructive recruitment failure and mass mortality of Pacific saury in the mid-1970s (Zhang and Gong, 2005).

Skipjack tuna (*Katsuwonus pelamis*)

Biology

Skipjack tuna is an epipelagic fish, occurring in waters ranging from 15° to 30°C. In the western Pacific, they have been captured as far north as 44°N off Japan, and as far south as 37°S off Australia (Forsbergh, 1980). However, in the eastern Pacific, they have been fished along the west coast of the Americas from 34°N off southern California to 27°S off northern Chile (Williams, 1970). This is due to the westward transport of warm surface waters and their poleward displacement along the western coast.

In warm equatorial water, skipjack tuna spawn year round. Sexual maturity may occur in fish as small as 40 cm in length (Matsumoto *et al.*, 1984). However, most fish appear to mature at larger sizes. Larger females produce significantly more eggs than smaller females, with the average adult producing 80,000 to 2 million eggs per year. Skipjack tuna feed primarily upon fishes, crustaceans, and mollusks. Cannibalism is common within this species as well. Their diet appears to be very broad and suggests an opportunistic method of feeding. Schools of skipjack are commonly found near convergences and upwellings.

Fishery

Skipjack tuna catches have been increasing at a rapid and fairly constant rate since the early 1970s. In the 1970s, the development of bait boat fisheries in Papua New Guinea and the Solomon Islands and the expansion of the Japanese distant-water, bait boat fishery led to the first large increases. In the 1980s, the development of large-scale purse seining in the Western Pacific Ocean (WPO) and the subsequent influx of vessels from several distant-water fishing nations resulted in further increases. In the 1990s, the policy of many canneries was not to buy tuna caught in association with dolphins, which has resulted in the relocation of many purse seiners to the WPO. This policy brought about further increases in the skipjack tuna catch in the WPO.

Korean fleets started to operate in the central WPO (WCPO) in the 1980 to 1981 season when large-scale purse seining developed in this area. Along with the increase in the number of fishing vessels, the fishing grounds expanded, and the catch increased. Since the catch first recorded over 100,000 t in 1990, it has increased to 174,000 t in 2002.

Climate and ocean effects

More than five major countries are catching skipjack tuna living in warmer waters other than in the WCPO. Korea is one of the major countries operating in these waters, along with Papua New Guinea, Japan, U.S., and Taiwan. The Korean catch was 153,328 t out of 823,849 t in total for the WCPO in 2003. Even though the Korean catch was not the main component of the total WCPO, (about 18% of total catch) the Korean data reflect a tendency similar to that of the whole WCPO data (R = 0.901**) (Fig. 68).

Korean fishing grounds have changed in time and space. As reported by Lehodey *et al.* (1997), computed longitudinal gravity centres of CPUE (G) from Korean fishery data were shifted toward the east during El Niño years (1986/87, 1991/92, 1997/98) (Fig. 69). The location of G and catch were compared with some environmental factors, such as the SOI, SST in NIÑO3.4, and SST in the main fishing ground (140°–170°E) to find some relationship between them. G shows a high correlation with ENSO factors: SOI (R = – 0.652*) and SST in NIÑO3.4 (R = 0.498*), and catch is significantly correlated with SST in the main fishing ground (R = 0.314*) (Table 30). Cross-correlation analysis with a time lag indicates that the evolution of the SOI and SST in NIÑO3.4 preceded the CPUE gravity center by four months (R = – 0.73**) and three months (R = 0.643**), respectively (table not shown).

There was no seasonality in the biological characteristics (length and GSI) of skipjack tuna. However, ENSO significantly affected skipjack length and maturation, though SST at 140–170°E (*i.e.*, distribution area of skipjack tuna) did not have influence. SOI and SST in NIÑO3.4 may have previously affected the fish length by 6 to 7 months ahead of time. Maturation was affected by environmental components about a year ahead.

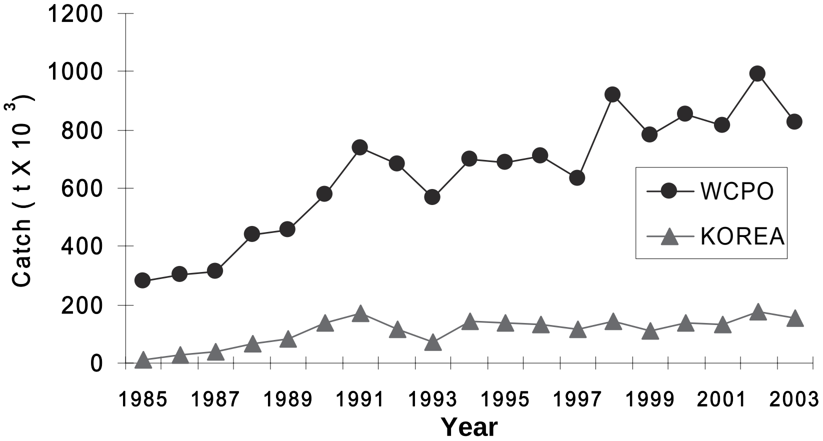


Fig. 68 Annual catches of skipjack tuna in the Western Central Pacific Ocean (WCPO) and Korea from 1985 to 2003.

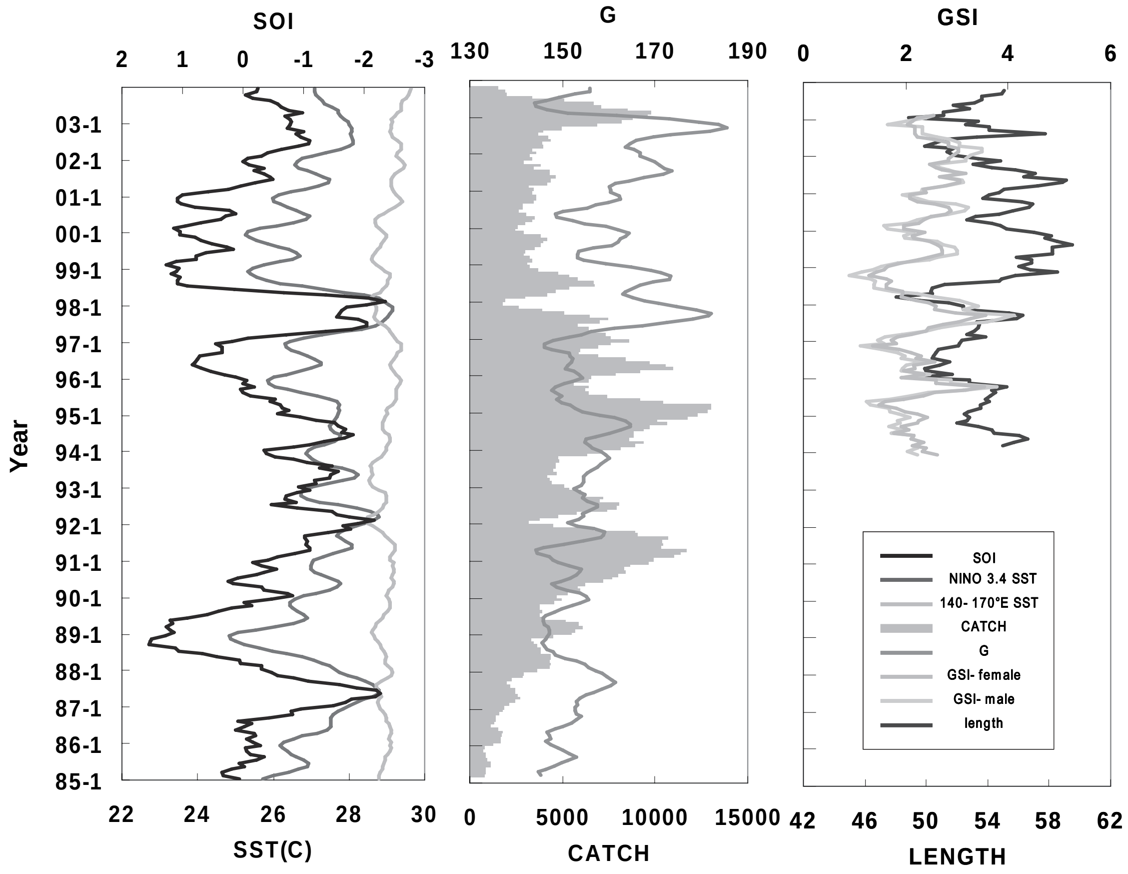


Fig. 69 Fluctuation of abiotic (SOI, SST) and biotic (G, catch (t), fork length (cm), GSI) factors with time. Monthly fluctuation of each factor was smoothed with a 5-month moving average. SOI, SST, G, and GSI represent the Southern Oscillation Index, sea surface temperature, computed longitudinal center of CPUE, and gonadal-somatic index, respectively.

Table 30 Correlation coefficients between environmental indices and fisheries/biological factors during the period 1985 to 1996. SOI, SST, NIÑO3.4, G, Catch, Length, and GSI indicate Southern Oscillation Index, sea surface temperature, the area confined by 5°N–5°S and 120–170°W, computed longitudinal center of catch per unit effort, monthly catch in the main fishing area, monthly mean fork length, and gonadal-somatic index, respectively.

	G	Catch	Length	GSI-male	GSI-female
SOI	– 0.652*	– 0.096	0.273*	– 0.350*	– 0.234**
SST in 140–170°E	– 0.252*	0.314*	– 0.193**	– 0.007	– 0.007
SST in NIÑO3.4	0.498*	0.107	– 0.367*	0.388*	0.254*

* P < 0.01, ** P < 0.05.

Common squid (*Todarodes pacificus*)

Biology

The life span of common squid is assumed to be 1 year (Nakamura and Sakurai, 1993), and their spawning season is spread throughout the year. As suggested for common squid in Japanese waters (Okutani, 1983; Yamada *et al.*, 1986), three spawning groups of common squid have been identified in Korean waters: summer (June–August), autumn (September–November) and winter (January–March) (Kim *et al.*, 1997). Male common squid mature about 2 months earlier than females. Females mature 2 or 3 weeks after mating. Once mature females spawn, they die (Yamada *et al.*, 1986; Ikeda *et al.*, 1993). Individuals are differentiated by mantle length, and the mantle sizes for winter, summer, and autumn spawning subpopulations have been measured at 24, 23 and 27 cm, respectively (Yamada *et al.*, 1986).

Stomach contents of the common squid consist of fish, cephalopods, crustaceans, algae, and unidentified matter. Fish are generally the most preferred prey. Although the major food items of summer and autumn populations are fish, those of the winter population are cephalopods. Algae and crustaceans are minor food sources. The three spawning groups seem to mix genetically, and contain the same stomach contents (Kim and Kang, 1998).

Fishery

In the East/Japan Sea, squid catches were at low levels (around 50,000 t) until the late 1980s, but increased rapidly after the early 1990s. Annual catches of squid ranged from 100,000 to 250,000 t during the 1990–2002 period (Fig. 70). The main fishing grounds of the squid angling fishery start to move to the north in the East/Japan Sea in April and to the south in September. The condition of common squid fishing largely depends on the fluctuation of water temperature in the southeastern coastal area. It is concluded that the high stability of water temperatures and the weak strength of cold water are the reasons for the good fishing conditions of common squid (Park *et al.*, 1998).

When catches were low in 1980s, the proportion of autumn spawners (*i.e.*, September and October) was the highest among spawning populations. However, as catches increased in the 1990s, the highest proportion of spawners shifted to November and December (Fig. 71). The increased catch from late autumn and early winter caused difficulties in distinguishing autumn and winter spawners. The amount of autumn catch was about double that of the winter catch during the 1980s, but catch levels were almost same in both populations during the 1990s. During the early 1990s, there was a rapid increase in winter catch while the autumn catch steadily increased (T. Sakurai, pers. comm.).

Climate and ocean effects

In the East/Japan Sea, squid catches increased continuously after the early 1990s. A correlation analysis was performed to evaluate the relationship between squid catch and zooplankton biomass (Table 31). In the northern and southern regions, the sum of squid catches from September to December is significantly correlated with zooplankton biomass except in two cases in the northern region: the sum of December (n – 1 year) and February, and February and April. The sum of zooplankton biomass in October and December in the n – 1 year showed the highest significant correlation with squid catches ($r = 0.864$ in the northern region and $r = 0.818$ in the southern region, $P < 0.001$). The squid catch is significantly associated with the abundance of euphausiids ($r = 0.578$ in the northern region and $r = 0.840$ in the southern region, $P < 0.05$) and amphipods ($r = 0.695$ in the northern region and $r = 0.648$ in the southern region, $P < 0.01$).

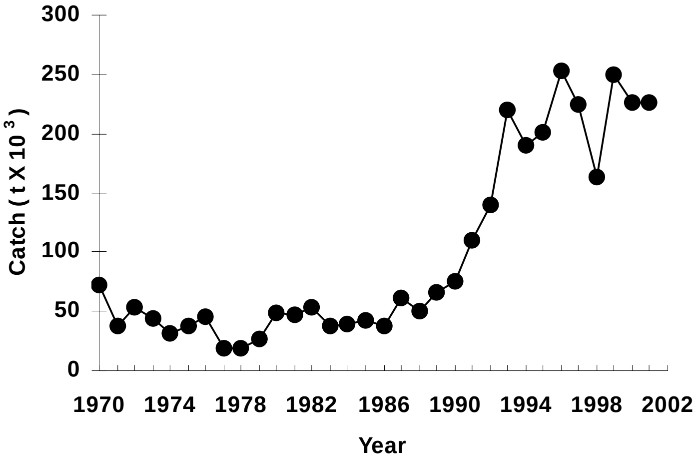


Fig. 70 Annual catches (t) of common squid in Korean waters from 1970 to 2002.

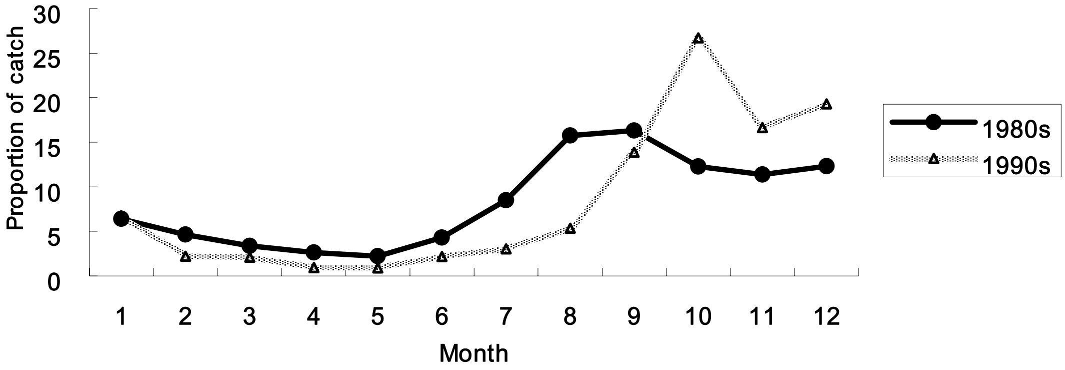


Fig. 71 Mean proportions of monthly catch of common squid in Korean waters during the 1980s and 1990s.

Table 31 Correlation coefficients between squid caught from September to December and zooplankton biomass in northern and southern regions in the East/Japan Sea (Kang *et al.*, 2002).

Variable of zooplankton biomass	Region	
	Northern	Southern
Sum of October and December (n – 1 years)	0.864***	0.818***
Sum of December (n – 1 years) and February (n year)	0.441	0.639**
Sum of February and April (n year)	0.402	0.654**
Sum of April and June (n year)	0.603**	0.679**
Sum of June and August (n year)	0.506*	0.575*

Correlation is significant at *0.01 < P < 0.05, **0.001 < P < 0.01, ***P < 0.001.

Variable	Region	
	Northern	Southern
Copepoda	– 0.188	0.152
Euphausiid	0.578*	0.840**
Amphipoda	0.695**	0.648**
Chaetognatha	0.371	0.496*

Correlation is significant at *0.01 < P < 0.05, **0.001 < P < 0.01.

Zooplankton biomass in October and December in the previous year showed a higher significant correlation with squid catches in September to December. Catch in October and December produced squid less than 10 cm in mantle size than in the previous year. Thus, zooplankton are more important for squid at the juvenile stage than for the adults, and it contributed to increased squid stocks after 1990. Of the four major zooplankton taxa, euphausiids and amphipods were significantly related with the squid catch. This shows that zooplankton, in particular euphausiids and amphipods, are very important for young squid in the East/Japan Sea. It is concluded that the most important factor for increased squid catches is increased zooplankton biomass, especially euphausiids and amphipods (Kang *et al.*, 2002).

Seawater temperature might be the most important parameter controlling stock abundance. When squid catches increased in the early 1990s, the SST in Korean waters increased at the same time. In particular, seawater temperature during winter seemed to be more important than during other seasons. When the winter temperature rose in 1990s, the winter population of common squid also showed a rapid increase compared to the autumn population.

Speculations on the Impact of Greenhouse Gas-induced Climate Change

This chapter speculates on the relationship between environmental changes and fish species in Korean waters. Environments are variable over time, and fish have a relatively routine life history. Fish spawning is influenced by some abiotic environmental factors, such as temperature, and their growth and survival are controlled by the abundance of prey and predators surrounding them. In order to figure out the ecological mechanisms, however, it requires extensive survey efforts, and a multi-disciplinary approach is essential to explain the relationship. In general, the marine ecosystems in Korean waters are varied and complex because large-scale climate events, such as ENSO, monsoons and the PDO, have an impact on water properties indirectly or directly. The fish species also exhibit numerous patterns of behavior. Oceanography and the biology of fish have not been extensively studied. Therefore, due to limited scientific knowledge, we are limited in explaining the relationship between climate change and marine ecosystems, including fish populations in Korean waters. Below is a brief speculation of the environmental impacts on major fish species around the Korean Peninsula.

Walleye pollock

Walleye pollock are a cold-water, demersal species and their spawning grounds in Korea are located at the southern limit of their distribution. They spawn in shallow bays off Korean Peninsula (Won-San Bay in the Democratic People's Republic of Korea), and juveniles might stay in the upper layer near the coastal areas. Although adults show demersal behavior, a future warming trend of SST might force fish distribution from south to north. The catch is traditionally made up of juveniles who would have to migrate into the fishing areas from the north. Furthermore, warming of the spawning grounds could be detrimental to the spawning adults, as well as to their early life stages. A general warming trend in the future, therefore, would probably result in low pollock abundance, although the impact of regimes would result in periods of cooler SST when pollock might return.

Chum salmon

Chum salmon are a cold-water species that stay in the surface layers of the ocean through most of their life cycle. Salmon hatcheries in Korea are at the southern range of their distribution and would be expected to be negatively affected by a warming of the ocean surface. Hatcheries could maintain a production of salmon fry, but ocean survival would be reduced, especially if there is higher seawater temperature at the timing of fry release. Production is affected by regimes which would suggest that there will be periods in the future when the marine survival of chum salmon would improve. However, a general warming trend in Korean waters would probably result in low chum salmon abundance and a low returning rate, even though climate/ environmental changes in the open ocean could also have a strong impact on the growth of chum salmon populations.

Small yellow croaker, hairtail, filefish

In the Yellow Sea, environmental conditions are influenced by many factors, such as the Kuroshio, seasonal monsoons and winds, and river runoff. Because of its shallow bathymetry, the Yellow Sea does not have truly demersal fish populations. However, in contrast to pelagic fish species, such as anchovy, some species (*e.g.*, small yellow croaker, hairtail, and filefish) locate in the relatively deep waters in the center of the southern Yellow Sea and the East China Sea.

The recruitment success of small yellow croaker is dependent upon seawater temperature, and consequently, catches would be improved 8 to 10 months later if warm and stable conditions formed at 75 m depth during the early life stages. However, the relationship between surface and bottom layers, and the cause–effect mechanism between environment and organisms have not been identified. There are too many unknown factors in the Yellow Sea ecosystem to determine the impact of warming on demersal fish species.

As we showed for small yellow croaker, it is not possible to speculate on the impact of global warming on demersal species, such as hairtail and filefish because the biology and ecology of these species is mostly unknown. One study on filefish indicated that catches were high in the 1980s and low in the 1990s. If the Aleutian Low intensifies under a global warming scenario, the volume transport of the Kuroshio would also increase which should favor improved filefish productivity. However, different fish species have different life cycles and habitat areas, and large-scale climate change might not show the same common effects for all fish species.

Anchovy, Japanese sardine, mackerels and common squid

In Korean waters, the portion of small pelagic fish species (anchovy, Japanese sardine, mackerels and common squid) has been increasing. In recent years, ten major small pelagic species have occupied 60 to 70% of the total catch, and common squid alone accounted for 20 to 25%. In many ecosystems around the world, abundance of anchovy follows trends that are opposite to those of the sardine. In Korean waters, however, an alternation between anchovy and sardine was not evident. There is improved larval survival and growth when the Tsushima Warm Current is strong near the coast of Korea, but it is not yet known what the relationship is between warming and Kuroshio strength.

There was a dramatic increase in sardine abundance after 1976, indicating that there are trends in abundance. The increase in abundance was related to an increase in the intensity of the Kuroshio and the increase in the plankton bloom in the autumn. One scenario for global warming forecasts is that there will be more frequent, intense Aleutian Lows which suggests that there will be more frequent periods typical of ocean conditions observed in the 1980s. If this is correct, periods of sardine abundance may be more frequent.

Chub mackerel and anchovy abundances increased in the mid-1990s, a period of high SST in December. ENSO might have an influence on seawater temperature in December. An elevated seawater temperature due to ENSO seemed to cause a high rate of growth and a good year class of those populations in Korean waters (Kim and Kang, 2000). In addition, there is clear evidence that climate, and climate shifts, affect the production of chub mackerel. More intense Aleutian Lows and a positive PDO may have a negative impact. Jack mackerel production follows a cyclic pattern of about 30 years.

There were large increases in the abundance of common squid in the 1990s when SST increased. If there are more frequent periods of intense Aleutian Lows, then abundance would decrease. However, if wind intensity is reduced and SST increased, then common squid will become more abundant.

Pacific saury

The abundance of Pacific saury is related more to the ENSO than to the PDO. The period of more frequent and intense El Niños in the mid-1990s appeared to be favorable for Pacific saury production. If wind intensity is reduced as a result of global warming, and El Niños become more frequent, Pacific saury production may increase. However, an intensification of the Aleutian Low may reduce abundance.

Skipjack tuna

ENSO evidently has an effect on skipjack tuna biology as well as its fishery. However, the relationship between ENSO and the global warming trend (*i.e.*, increase in greenhouse gas) is not clearly understood in tropical waters.

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Russia

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The Fishery

Total catch of marine commercial resources in the Russian Exclusive Economic Zone (EEZ) increased from 1980 until 1986, and then declined (Table 32). In 1988, there were large landings of two highly abundant species: walleye pollock and Pacific sardine. These two species made up about 80% of the Russian total catch in the 1980s. In general, the late 1980s and early 1990s were years of high abundance of walleye pollock and sardine stocks. In the 1990s walleye pollock stocks declined, resulting in a general decline in catches. In 1992, no Pacific sardines were harvested commercially in the Russian EEZ as a result of a natural decline that was related to changes in the climate and ocean. Pacific herring catches grew from 2.5 to 25% from 1985 to 2000 as a result of an increase in herring stock abundance in 1990. In the late 1990s, the share of pink salmon catch increased 2 to 3 times compared to 1980s, and constituted 9% of the total catch. Variability in catch data for other fishes was also observed, *e.g.*, during 1985–2000, the share of flatfishes and cod increased in the total catch.

In this report we consider how climate and ocean conditions have affected the abundance and catch of key species in the fishery since 1980 (Table 33). From 1980 until about the mid-1990s, the species examined here represented over 80% of the catch. In the early 1990s, they represented larger percentages of the catch, exceeding 90% of the total catch (Table 33).

Climate and Ocean Influences

Inter-annual, decadal, and long-term variability in the climate and ocean cause considerable rearrangements in marine communities. Historically, there were warm and cold periods. Assuming long-term variability with natural cycles lasting hundreds of years, the last large cold period was 13 to 18 centuries ago (a small "ice age"). The average global temperature has risen gradually since the mid-19th century (Fig. 72). In this case, the 20th century belongs to the recent warm epoch. Shorter

Table 32 Total catch (t) of all marine fishes off the Pacific coast of Russia (FAO data).

Year	Catch
1980	3,200,111
1981	3,501,358
1982	2,927,611
1983	4,139,148
1984	5,351,074
1985	5,351,074
1986	5,701,672
1987	5,357,587
1988	5,198,130
1989	4,838,540
1990	4,363,064
1991	3,867,734
1992	3,144,203
1993	2,673,173
1994	2,192,418
1995	2,733,097
1996	2,979,211
1997	3,004,145
1998	2,839,042
1999	2,414,667
2000	2,190,343
2001	2,010,554
2002	1,554,057

cycles of 2 years to decadal periods can be distinguished within these longer cycles. It is very important to take into account natural cycles of both short-term and longer duration to properly forecast future changes (Shuntov, 2001). Some data show that 40- to 60-year-long cycles can be of primary importance (Klyashtorin and Sidorenkov, 1996; Shuntov *et al.*, 1997). These cycles significantly influence the environment, providing inter-decadal faunal changes and long-term fluctuations in various species. Shorter cycles may also have an impact on marine communities and species dynamics, but their effect is much smaller.

In the last century, the first period of warming lasted 30 years, from 1920 to 1940. At that time, summer seasons could be described as the first "sardine epoch" of the 20th century. Large-scale migrations of subtropical, and even tropical, fishes and other southern species occurred into the Far Eastern temperate waters.

The second period of warming lasted from 1970 to the 1980s. These years were characterized by the second rise in Pacific sardine abundance, and by warm-water species migrations to the Far Eastern region. During that period, the temperature was generally higher than in the 1920s and 1930s (Fig. 72).

Table 33 Catches (t) of key species in the Russian fishery and total catch as a percentage of the total catch of all species (FAO, 2000).

	1980	1985	1990	1995	2000
Pink salmon	77,367	85,976	71,374	139,369	132,851
Chum salmon	14,556	20,556	23,602	12,632	21,944
Sockeye salmon	1,629	3,260	5,177	5,998	12,676
Walleye pollock	2,111,669	3,343,034	2,863,937	2,208,410	1,215,065
Pacific herring	79,251	189,584	97,357	116,787	361,241
Pacific saury	38,600	23,423	72,618	25,140	17,390
Pacific sardine	359,289	748,158	879,393	0	0
Pacific cod	23,346	188,443	121,397	100,730	68,415
Total	2,710,187	4,602,434	4,134,855	2,609,066	1,829,582
Total all species	3,200,111	5,351,074	4,363,064	2,733,097	2,190,335
% of total of all species	84.6	86.0	94.8	95.5	83.5

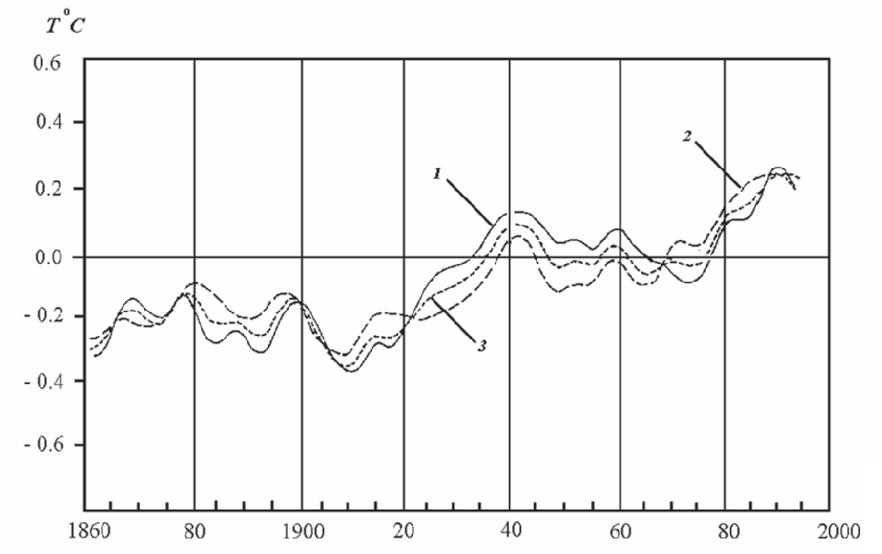

Fig. 72 Anomaly of integrated temperature over land and ocean surface temperature from 1880 to 1993: 1 indicates northern hemisphere, 2 indicates southern hemisphere, and 3 refers to global (Halpert *et al.*, 1994).

The last warm period was longer, with a gradual rise in temperature (Fig. 72). Recently, marine communities have become influenced by a temperature decline that started in the mid-1990s. At the same time, the average global temperature remains high. Pacific sardine abundance decreased in the early 1990s. Considerable rearrangements in nekton and plankton communities of the Far Eastern seas were noticed at that time (Shuntov, 1986; Klyashtorin and Sidorenkov, 1996; Shuntov *et al.*, 1997).

There are a lot of arguments in favour of both global warming and cooling. A compromise might be to describe it as, "cooling on the background of global warming" (Anonymous, 1993), which does not either support or refute the concept of greenhouse gas-induced climate change. This compromise in wording suggests that there can be an interaction between climate cycles of different duration and character.

In the 20th century, the human impact on nature started to have a negative on the environment. As a result, numerous investigations of the anthropogenic influence on climate took place. In these studies, the greenhouse effect that resulted from carbon dioxide increase in the atmosphere, as well as other sources of air pollution, was considered. The effect of these factors on temperature can be mutually exclusive. Speaking of the human impact on climate change, we should also keep in mind that there were warm periods even greater than the recent one in the history of the Earth. Climate changes that historically appeared as alterations of warm and cold periods are proceeding as natural cycles with regional features (Shuntov, 2001). This was observed in the Far Eastern seas at the brink of the 20th and 21st centuries. Cyclic changes in atmospheric processes over, and ice conditions in, the Far Eastern seas have shown that after the very hot year of 1997, ocean temperature cooled in the Far Eastern seas (Glebova, 2002). Most data sets were obtained during TINRO-Centre research cruises in the Okhotsk Sea, the main area for Russian commercial fishery operations (Shuntov *et al.*, 2002). After 1997, considerable cooling was observed judging from average water temperature (Table 34), ice conditions (Fig. 73), and the extent of cold areas (Figs. 74 and 75). Similar trends were observed in the western Bering Sea where the late 1990s, as well as 2001 and 2002, were relatively cold (Radchenko, 2001; G.V. Hen and others, pers. comm.). Environmental processes were not always synchronous in the northwestern and southwestern parts of the sea, which also showed considerable annual variability. Around the Kuril Islands (Fig. 76), variability patterns, including circulation and temperature, were different from the adjacent Okhotsk Sea area. In some years that were cold in the northern Okhotsk Sea, there were positive temperature anomalies along the Kuril Islands (Samko and Novikov, 2002).

Key Species in the Fishery

Pink salmon (*Oncorhynchus gorbuscha*)

Biology

Pink salmon are the most numerous among the Pacific salmon species, constituting about 40% of the biomass and 60% of the number of total salmon landings in the North Pacific Ocean. Pink salmon have the shortest and simplest life cycle. As soon as the fry leave their spawning sites, they migrate downstream into the sea where they grow first in the coastal areas and then in the central North Pacific Ocean. After 12 to 14 months, maturing individuals come back to their native rivers to spawn and die.

The freshwater natural habitat of pink salmon includes Asian and North American rivers north of approximately 40°N. Pink salmon are distributed north of 40°N in the sea, and dwell in southern areas in winter. In spring, as soon as the water warms, they move northward to their spawning streams. The spawning period lasts from June to November, depending on the region.

Table 34 Average water temperature (°C) at 50 at 200 m depth on the western Kamchatka shelf (April) and in the northern Okhotsk Sea (May–June) from 1996 to 2000 (Ustinova *et al.*, 2002).

Region	1996	1997	1998	1999	2000
Western Kamchatka shelf	0.40	1.13	0.01	– 0.25	– 0.28
Northern Okhotsk Sea	– 0.45	– 0.12	– 0.72	– 0.94	– 0.98

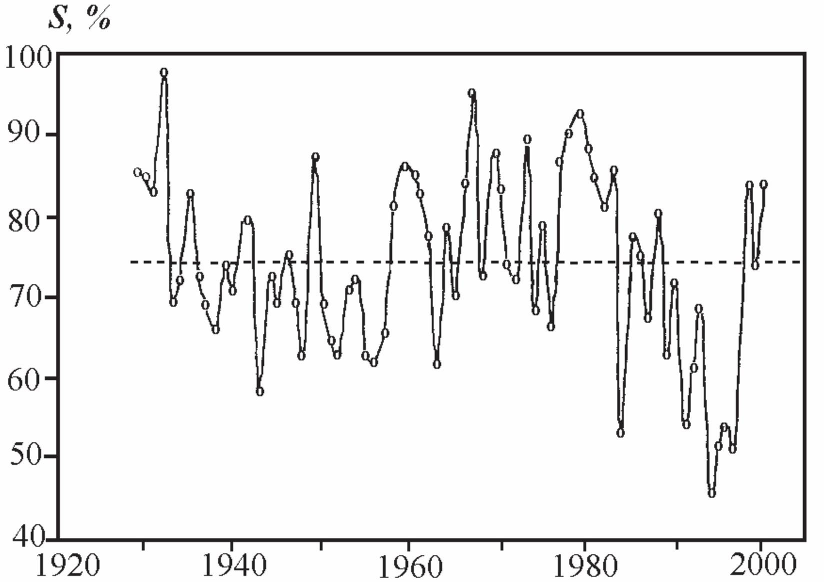

Fig. 73 Ice conditions in the Okhotsk Sea in March and the average long-term value (dashed line) (Ustinova *et al.*, 2002).

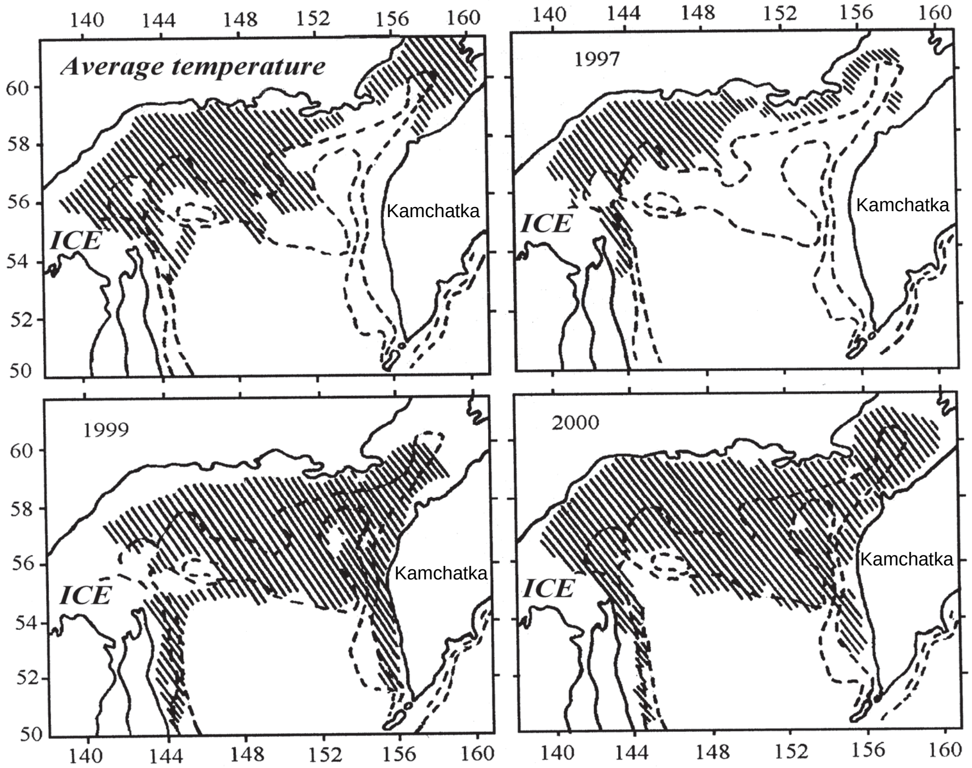

Fig. 74 Distribution of subsurface cold waters (shaded area) with temperatures less than 1°C in the core of the cold intermediate layer for the Okhotsk Sea in May–June (Khen *et al.*, 2002). Dashed lines indicate bathymetry.

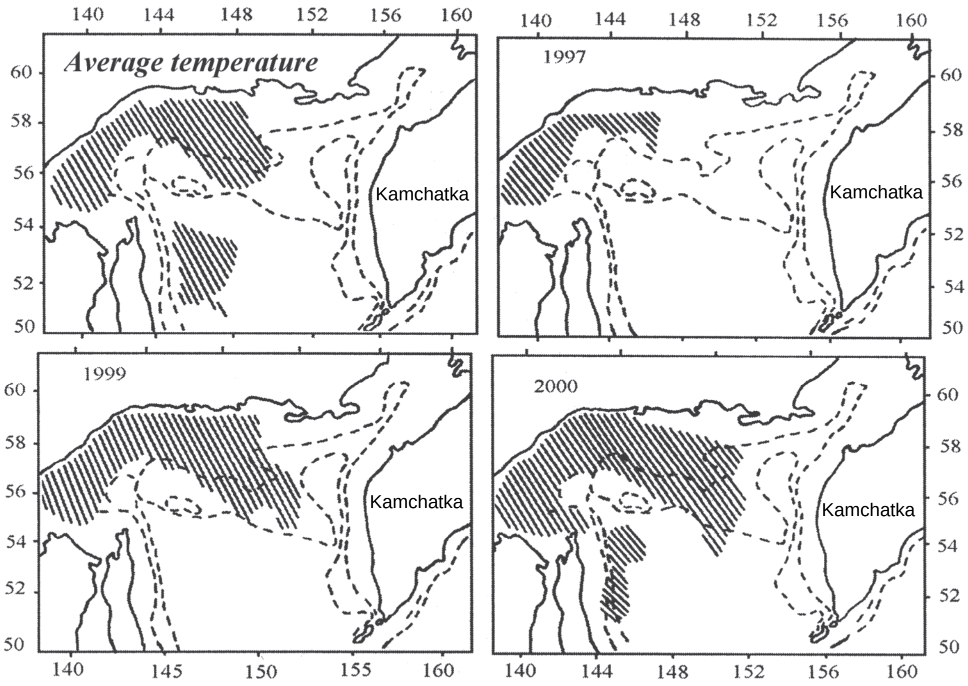

Fig. 75 Distribution of subsurface cold waters (shaded area) with temperatures less than 1°C in the core of the cold intermediate layer for the Okhotsk Sea in September (Khen *et al.*, 2002). Dashed lines indicate bathymetry.

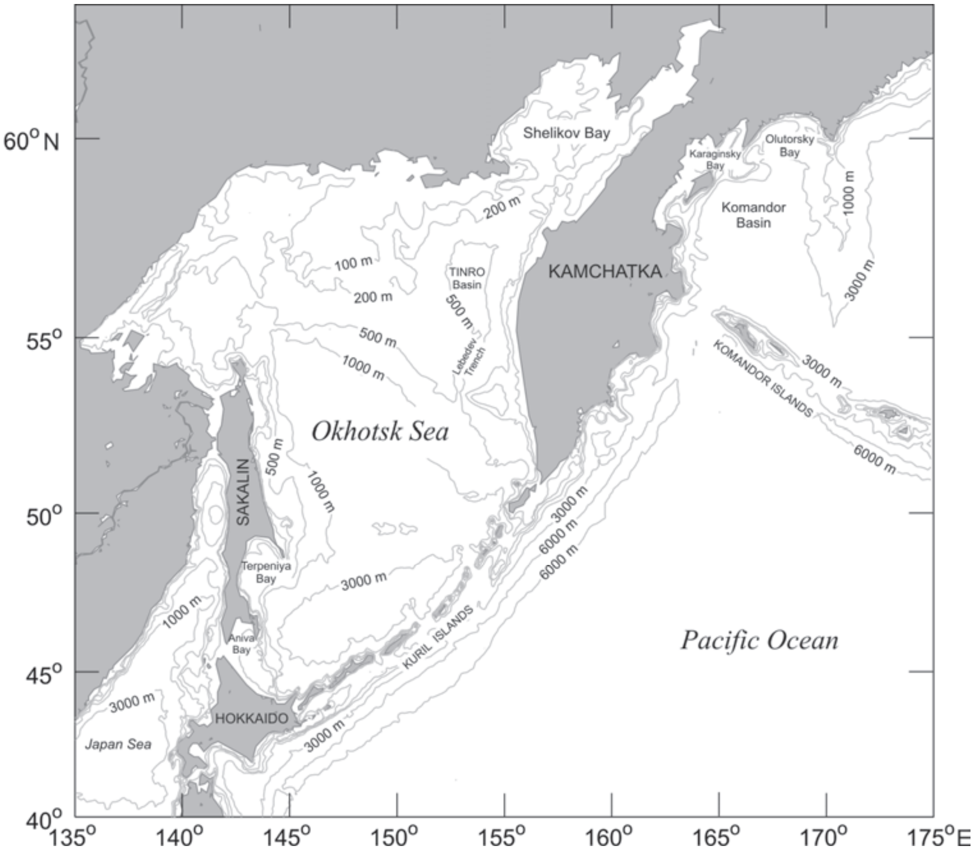

Fig. 76 Map of the Okhotsk Sea and Kamchatka area.

Pink salmon differ from other Pacific salmon species because (1) they have a 2-year life cycle; (2) mature individuals are the smallest of all the species, (1.0 to 2.5 kg, on the average); (3) young fish leave the spawning sites and migrate downstream immediately after hatching (chum salmon also behave this way), and (4) mature males possess a distinctive hump. The 2-year cycle results in reproductively isolated generations of odd and even years that may differ in abundance. Today, in eastern Kamchatka, odd-year generations of pink salmon are more numerous, while in western Kamchatka even-year broods are more abundant. However, this odd- and even-year behaviour can change and deviations from the 2-year life cycle may occur. Unlike other Pacific salmon species, pink salmon do not conduct long-distance spawning migrations up rivers. Most reproduce close to the river mouth, usually within 10 km of the ocean. The homing instinct is rather weakly developed in this species, and some individuals can stray for several hundreds, and even thousands, of kilometres away from their native places. Pink salmon individual fecundity varies from 900 to 2,700 eggs, with an average range of 1,300 to 1,600 eggs.

Fishery

Pink salmon are fished only in the coastal areas of Russia. Most of the fish are harvested as they migrate along the shoreline and approach their natal rivers. Large stationary traps are usually placed along the coast near the spawning river mouths, with a lead stretching from the shore area to the trap. Pink salmon catches increased in the 1980s and 1990s for both even- and odd-year runs (Table 35). Even-year catches were largest in 1998 as were odd-year catches in 1991; however, catches have remained high relative to the early 1980s. Landings of pink salmon in the Russian EEZ (Fig. 77) from 1971 to 2002 show that during the last 5 odd years, reserves have remained at a high level. The average annual catch for odd years is about 128,000 t. The biggest catches of pink salmon for odd years take place in three areas: eastern Kamchatka, and the eastern Sakhalin and southern Kuril islands. The rivers on the west coast of the Okhotsk Sea provide a considerable contribution to the total catches. During the last 2 odd years in particular, catches of pink salmon have increased on the eastern coast of Sakhalin Island.

Table 35 Pink salmon catches (t) off the Pacific coast (FAO and NPAFC data).

		NPAFC[1]	
Year	**FAO**	**Russia**	**Asia**
1980	77,367	79,300	99,700
1981	79,813	87,900	113,600
1982	42,157	47,800	68,600
1983	96,270	107,700	133,000
1984	50,537	56,700	75,500
1985	85,976	96,400	123,700
1986	37,988	41,000	56,700
1987	92,311	98,800	118,200
1988	36,808	40,700	56,500
1989	144,748	149,600	167,200
1990	71,374	76,100	88,900
1991	216,124	211,900	230,800
1992	79,414	87,300	107,400
1993	104,855	113,000	138,000
1994	117,533	126,300	157,200
1995	139,369	148,300	172,600
1996	104,377	110,900	143,700
1997	169,070	190,200	206,100
1998	177,382	193,000	218,200
1999	158,560	188,500	205,300
2000	132,851	148,600	175,400
2001	149,421	171,200	181,600

[1] Eggers *et al.* (2003); NPAFC – North Pacific Anadromous Fish Commission

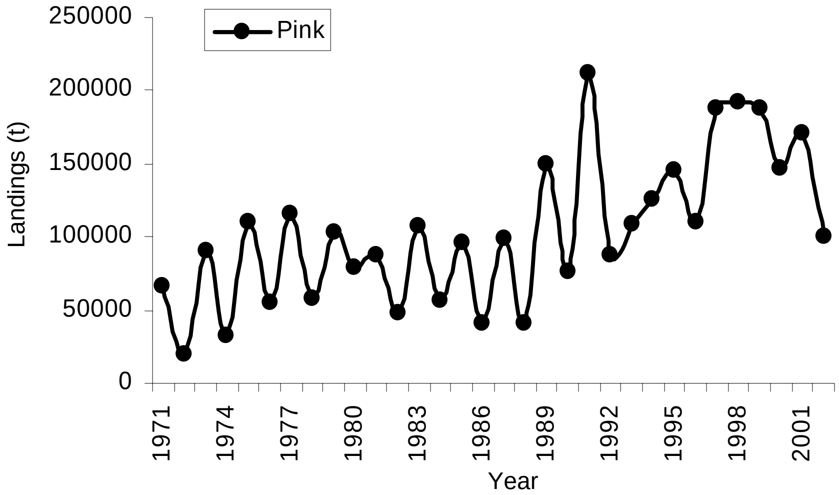

Fig. 77 Annual landings (t) of pink salmon in the Russian Exclusive Economic Zone (EEZ).

Climate and ocean effects

In the 1990s, the dynamics of climatic processes over the North Pacific appear to have become unfavourable for salmon production (Beamish and Bouillon, 1993; Chigirinsky, 1993). However, pink salmon are the most difficult of all the salmon species to forecast future runs. Currently, the even-year stocks are very productive in western Kamchatka and in the southern Kuril Islands; if this situation continues, a return comparable to the high harvest levels of 1920–1930 could occur (Radchenko, 1998).

Chum salmon (*Oncorhynchus keta*)

Biology

Asian chum salmon consist of numerous reproductively isolated local populations that differ in some biological traits. The population structure is complicated by geographical differences and seasonal races. Young chum salmon migrate early from the spawning grounds, mostly as fry, though some migrate later. In Kamchatka, the fry migrate from early April to July, with a peak in mid-May to early June. In the Anadyr River, fry begin downstream migrations in late May to early June. In the northern Okhotsk Sea, fry migrate from May until June, with a maximum run in early June.

In summer, in the coastal areas of the Russian Far Eastern seas, juveniles are present from late July until early August. Yearlings migrate to the southeastern Bering Sea by late November. While in the southern Okhotsk Sea, they may feed until early winter because of favourable hydrologic conditions. In the Okhotsk Sea, the yearlings feed primarily on amphipods (*Themisto japonica* and *Primno abissalis*) and euphausiids (*Thysanoessa longipes* and *Euphausia pacifica*). Pteropods, copepods, and tunicates are of less importance in their diet.

During the winter–spring feeding period in the open ocean, chum salmon live primarily within the area of subarctic and subtropical water masses, where the temperature ranges from 3° to 11°C. By late May, age 2+ chum salmon migrate back to the Kuril, Aleutian and Komandor islands and enter the Okhotsk and Bering seas. The Bering Sea serves as the main feeding area for immature fish during the summer, while the Okhotsk Sea is less important. In general, the distribution of older chum salmon in the Far Eastern seas during summer–autumn is as follows: large immature fish stay in the coastal regions; age 2+ and older immature fish are located over the slope and outer-shelf areas, while 2-year-old fish are offshore over deep-water basins.

Chum salmon range in age from 2 to 6 years old. There are mostly 3+ (sometimes 4+) fish among those returning to spawn. Spawning fish of ages 1+, 2+ and 5+ are rare in Asian rivers. The average weight of age 3+ and 4+ chum salmon from the summer spawning run range from 2.90 to 3.75 kg, and from the autumn spawning run, from 3.6 to 5.4 kg.

A survey conducted in chum feeding regions has shown that the temperature range for this species is much wider than was considered previously, ranging from 1.5° to 20°C. In the first year of marine life, chum salmon prefer water colder than 10.8°C. Older fish have been observed in warmer waters. Mature fish can be found beyond these limits, and can dwell not only in the surface layer but can also migrate within a wide depth range. The number of immature fish feeding in the Okhotsk and Bering seas depends on the extent of Pacific water advection. When the inflow of the Pacific waters into the seas is weak, the immature chum migrations are also small, and vice versa.

Chum salmon are not necessarily a typical planktivorous species in the Far Eastern seas. In summer they often feed on nekton, including mostly young pelagic, and occasionally, mesopelagic fishes. In the Bering Sea, they feed mainly upon pteropods. In the Okhotsk Sea, they prefer pteropods in reproductive areas and in areas with dense aggregations of these molluscs. For zooplankton diet, chum salmon prefer euphausiids. Gelatinous plankton dominates in mature chum salmon stomach contents in the Okhotsk Sea, which could be related to their physiology.

Fishery

From the early 1950s to the mid-1970s, the Russian harvest of chum salmon decreased. This decrease was gradual but rather significant and was undoubtedly connected to the depleted condition of the Russian chum salmon stocks. A slow recovery of chum salmon stocks occurred in the 1980s, but during the 1990s these stocks began to decrease again (Table 36). It is believed that competition with the chum salmon juveniles of Japanese hatchery origin during the marine rearing phase has prevented recovery of the wild Russian chum salmon stocks to some degree.

Sockeye salmon (*Oncorhynchus nerka*)

Biology

Sockeye (also known as red) salmon reproduce in the rivers flowing into the Pacific Ocean and its northern seas from northern Hokkaido to the northern Bering Sea along the Asian coast (Bugaev, 1995). They enter spawning rivers from mid-May until September, depending on the region. Upon entering a river, pre-spawning fish may stay there as long as 1 month, and up to 1–2 or 3–4 months in lakes before spawning. There are well-defined seasonal stocks of sockeye salmon that have different spawning times. The differences may be as much as 15 to 20 days. In the Asian sockeye populations early (spring) and late (summer) runs occur. Spawning grounds are confined to rivers, and lakes with groundwater springs. Spawning time depends on the average temperature for the incubation of eggs: the higher the temperature, the later the spawning time (Brannon, 1987; Burgner, 1991). Embryonic and larval development takes from 5 to 8 months. The hatching period can be extended, depending on spawning time and temperature in the spawning grounds. Most sockeye salmon rear in fresh water for at least 1 year. Beginning from the larval stage, the species exhibit shoaling behaviour. The freshwater period of young sockeye from different stocks lasts from 1 to 4 years. Fry with a yolk sack start feeding mainly upon benthic organisms that they find on the spawning grounds. Pelagic yearlings consume primarily zooplankton.

Table 36 Chum salmon catches (t) in the Russian EEZ (FAO and NPAFC data).

Year	FAO	NPAFC [1]
1980	14,556	17,600
1981	12,914	17,000
1982	10,840	15,700
1983	18,980	23,900
1984	9,622	15,200
1985	20,556	27,900
1986	21,480	25,600
1987	16,640	29,800
1988	24,532	29,100
1989	15,160	25,400
1990	23,602	30,400
1991	12,640	22,000
1992	14,060	21,600
1993	12,610	31,600
1994	14,603	42,500
1995	12,632	47,000
1996	16,413	39,600
1997	15,899	32,000
1998	18,737	37,100
1999	20,025	36,300
2000	21,944	42,200
2001	17,940	37,500
2002	22,698	–

[1] Eggers *et al.* (2003),
NPAFC – North Pacific Anadromous Fish Commission

In most cases, sockeye salmon migrate to the sea at age 2, and rarely at age 3. Smolts stay in coastal waters before migrating offshore in fall. Sockeye salmon feed mainly on plentiful crustaceans, pteropods, and small pelagic fish. Survival, growth, and migration patterns of the fish during during their marine period largely depend on conditions within feeding areas and stock abundance.

Fishery

Stocks of Pacific salmon species along the Asian coast are harvested by driftnet, set in coastal areas and rivers. Catch statistics for the Russian and Asian fisheries are usually combined into a total for all "Asian" catches (Table 37). However, driftnet data are considered separately in Table 37 because it is difficult to estimate the origin of fish in high-seas catches. Asian sockeye salmon catches were low in the late 1940s through to the mid-1950s. From the mid-1950s to the mid-1980s catches were 1,150 to 5,590 t. In 2002, total sockeye salmon landings were 22,800 t, close to maximum catches taken in the 1920s and 1930s when 14,570 to 39,750 t of sockeye salmon were annually harvested.

Climate and ocean effects

Catch statistics for sockeye salmon generally follow the trend for combined Pacific salmon landings in Asia and North America (Klyashtorin, 1998; Klyashtorin and Rukhlov, 1998; Radchenko, 1998), suggesting that similar factors may influence the abundance of different Pacific salmon species. Judging from the literature, the most significant factors are: climate regimes, food competition, fishery pressure, and ecosystem rearrangements of biological communities (Radchenko and Rassadnikov, 1991; Shuntov *et al.*, 1997; Klyashtorin, 1998; Klyashtorin and Rukhlov, 1998; Bugaev and Dubynin, 2002).

Table 37 Sockeye salmon catches (t) off the Pacific coast (FAO and NPAFC data).

		NPAFC[1]	
Year	**FAO**	**Russia**	**Asia**
1980	1,629	3,900	–
1981	1,534	3,800	–
1982	1,335	3,000	–
1983	1,425	4,300	–
1984	5,082	6,300	–
1985	3,260	9,300	–
1986	3,577	7,500	–
1987	4,922	11,900	–
1988	5,099	8,400	–
1989	3,003	9,700	–
1990	5,177	16,400	–
1991	6,279	14,400	–
1992	6,408	15,400	–
1993	5,490	14,000	21,700
1994	5,658	10,700	14,400
1995	5,998	14,200	20,300
1996	13,630	16,800	22,400
1997	6,698	9,000	18,100
1998	8,820	10,100	12,800
1999	7,792	11,900	14,600
2000	12,676	15,100	17,200
2001	10,369	18,100	20,800
2002	14,701	–	–

[1] Eggers *et al.* (2003); NPAFC – North Pacific Anadromous Fish Commission

There are two important points regarding the influence of global physical factors on production and size of salmon catches. First is the influence of the quantity of atmospheric condensation and air temperatures, especially during the winter period in spawning areas. Second is the influence of atmosphere circulation through change in the scheme of the mass transfer of water in areas of forage migration during the sea period of salmon. In ontogenesis, salmon are influenced by various natural factors that influence orientation and production. Changes in water mass transfer in the North Pacific sector and increases in zooplankton production are some of principal causes of changes in salmon production. During the periods of a more southern position of the subarctic front and intensive distribution to the south of the subarctic waters, annual catches of all species of salmon are higher than average.

Walleye pollock (*Theragra chalcogramma*)

Walleye pollock are a highly valuable commercial species in Russia. They are widely distributed in the pelagic zone in the Russian Far Eastern seas. Major stocks of are fished in the Okhotsk Sea and western Bering Sea.

Okhotsk Sea pollock

Biology

Walleye pollock are the most numerous commercial fish in the Okhotsk Sea. During high abundance, they occur throughout almost the entire sea, from shallow coastal shelf areas to deep-water basins in the south and central parts of the sea Fig. 76). Walleye pollock have a vertical distribution range from the surface down to the lower mesopelagic layers. When abundance is low, walleye pollock are restricted to the shelf and continental slope. Medium-aged mature pollock are characterized by the greatest migratory activity. During their first 2 years of life, they remain within their spawning areas, while older fish feed mainly in the northwestern part of the sea, over the slope of the TINRO Basin (Fig. 76). On the western Kamchatka shelf, their reproductive period lasts from February until late June, with a peak in March and early April. In the northwestern areas, the peak shifts to later in the year. In Shelikhov Bay, the spawning peak is in late April; in the Taui region, it is from late April to early May; on the eastern Sakhalin shelf, it is in early June. Eggs, larvae and yearlings are distributed within spawning areas. Patterns of both spawning and early developmental stages are related to water dynamics, particularly to quasi-stationary anticyclonic eddies that retain eggs and larvae and prevent them from being transported over large areas. The areas of walleye pollock concentration are also areas where small copepods aggregate. Copepod eggs and nauplii are the main food sources for pollock larvae and juveniles. By fall, the young fish start to feed on euphausiids, along with copepods. Mature walleye pollock are practically euryphagous, although copepods and euphausiids remain the primary prey. Individuals over 60 cm in length live mostly near the bottom, leading a nektonic way of life, and at this stage, nektonic and benthic prey play an important role in walleye pollock feeding.

At age 2 years, western Kamchatka pollock begin to migrate to near-slope areas, primarily in northern and northwestern directions, to the TINRO Basin and Lebedev Trench[1] where they dwell, conducting short seasonal migrations until maturation. Males normally mature at 5 years, with an average length of 35 to 36 cm, and females mature at the age of 6 with a length of 37 to 39 cm. The sex ratio is generally 1:1, and remains that way until age 6 to 7 years, when the percentage of females increases. In older age groups (14–17 years), males are found only occasionally, suggesting that females live longer than males.

Individual fecundity of the Okhotsk Sea pollock varies considerably, ranging from 30,000 to 40,000 eggs in first maturing females to 1.3–1.5 million eggs in older, larger fish. The average absolute individual fecundity is within 150,000 to 270,000 eggs per female. Gonads mature in a continuous and synchronous manner. Several medium-aged groups (5–8 years) make up the basis of exploitable stock, and the proportion of older fish is small. The maximum age of Okhotsk Sea pollock is 21 years, as determined from the aging of scales.

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[1] For alternate spelling and for additional information on place names, refer to PICES Scientific Report No. 8 on *Multilingual Nomenclature of Place and Oceanographic Names in the Region of the Okhotsk Sea.*

Fishery

Walleye pollock catches in the Russian EEZ are given in Table 38. The largest portion of this catch was landed in the Okhotsk Sea (Fig. 78). The largest catches were related to the appearance of average and strong year classes.

Climate and ocean effects

The population dynamics of the Okhotsk Sea pollock has been studied only since the recent commercial development of the species. Beginning in the 1970s, walleye pollock abundance fluctuated with a regularity related to 11-year cycles of solar activity and 8- to 10-year cycles in atmospheric processes. Cyclic patterns in the variability of walleye pollock abundance are achieved through long-term changes in marine ecosystems, and by reorganizations in pelagic communities caused by water and heat exchange between the Okhotsk Sea and the Pacific Ocean. The appearance of strong walleye pollock year classes coincides with the extent of moderately warm circulations of water. Stock abundance increases along with macro-zooplankton biomass during the warming of the Okhotsk Sea. Such periods of warming were observed during global climate changes in the middle 1970s, 1980s, and 1990s. The main factor in determining the survival of the Okhotsk Sea pollock progeny during their critical stages of development is the amount of food supply available. The direct impact of climate and oceanographic factors (such as storm wind intensity, extent of ice cover, and water and air mass conditions) on the survival rate at early ontogenetic stages, when the strength of age classes is formed, is less important.

Table 38 Walleye pollock catch (t) in the Russian Exclusive Economic Zone (EEZ; FAO data).

Year	Catch
1980	2,111,669
1981	2,137,875
1982	2,497,907
1983	2,747,044
1984	3,449,559
1985	3,343,034
1986	3,584,140
1987	3,421,719
1988	3,369,858
1989	3,133,152
1990	2,863,937
1991	2,495,808
1992	2,340,700
1993	2,114,456
1994	1,746,629
1995	2,208,410
1996	2,439,980
1997	2,252,742
1998	1,930,650
1999	1,500,450
2000	1,215,065
2001	1,145,016
2002	826,707

Bering Sea pollock

Biology

Walleye pollock are the most abundant gadoid fish species in the Bering Sea. There are reproductively isolated populations of the species in the eastern and western Bering Sea. There is evidence that the "basin" pollock, which spawn in the deep-water region off the eastern Aleutian Islands, and the "shelf" pollock, which spawn in shelf areas, belong to independent reproductively isolated stocks, with possible genetic differences. Reproduction of the eastern Bering Sea pollock takes place in a vast area from the central Aleutian Islands (Kanaga Sound) and southeast shelf (Unimak Island and Pribilof Islands area) up to the north in Anadyr Bay, with the main spawning grounds located in the southeastern Bering Sea. The western Bering Sea pollock spawn in the Olutorsky and Karaginsky bays (Fig. 76), and adjacent southern part of the Koryak coast. Each large spawning stock consists of smaller groups that differ in age composition, time of active spawning, behaviour, and distribution patterns for feeding and pre-spawning fish.

Biomass of eastern Bering Sea pollock was estimated at 8.6 million t; biomass of western Bering Sea pollock was assessed as 286,000 t using echo integration midwater trawl and bottom trawl surveys in 2002.

The spatial distribution range of both mature and immature walleye pollock usually expands significantly during their feeding period. Eastern Bering Sea pollock migrate to the northwestern Bering Sea shelf and deep-water Aleutian basin. The extent of the eastern Bering Sea distribution in the Aleutian basin depends on the population biomass and abundance of "basin" pollock.

Western Bering Sea pollock migrate from their spawning area in Olutorsky and Karaginsky bays to the northeast, where they are distributed off the Koryak coast and in Cape Navarin area in summer and fall. Some older fish are found in the Komandor Basin.

Eggs and larvae of the eastern Bering Sea pollock are carried away by currents from the spawning grounds near Bogoslof and Unimak islands into the Bristol Bay and Pribilof Islands area. Eggs and larvae can presumably drift from the Pribilof Islands spawning grounds into the northwestern Bering Sea.

Walleye pollock first mature at age 3+ (30% of the fish), and at 5 years old the majority of fish (about 85%) are mature. Most walleye pollock in the fishery are 3 to 8 years old. Natural mortality increases sharply in fish older than 8 to 9 years. Fish of about 24 to 25 years old are extremely rare in the Bering Sea population.

Generally, individuals from the northwestern Bering Sea are slightly smaller at age than those from the southeastern area. There are certain growth rate differences by sex, areas, and year classes.

Fishery

The walleye pollock fishery started about 1970 in the Russian EEZ of the Bering Sea. During the 1970s, walleye pollock were basically fished out in the western seas (Karaginsky and Olutorsky bays). The highest catch took place in 1972 when it exceeded 2 million t. The second highest catch was in 1988 when 1.3 million t were caught in Russian waters. On the western shelf of the Bering Sea (west of 174°), high and stable catches were observed from 1976 to 1994. Catches averaged 273,000 t a year (549,000 t maximum). From 1995 to 2002, the annual catch decreased 3.2 times (the maximum in 1999 was 149,000 t).

Climate and ocean effects

Abundance and biomass of Bering Sea pollock year classes vary significantly, depending on climate changes and oceanographic conditions during the spawning period. Larval and juvenile survival may depend on the direction of currents, activity of eddies, frequency of storms, water turbulence, temperature and salinity gradients in the upper water layer, as well as on food supply. The drift of pollock larvae into the coastal waters of Bristol Bay and Pribilof Islands has potentially positive impacts on their survival, because in coastal areas, oceanographic conditions are more stable and the

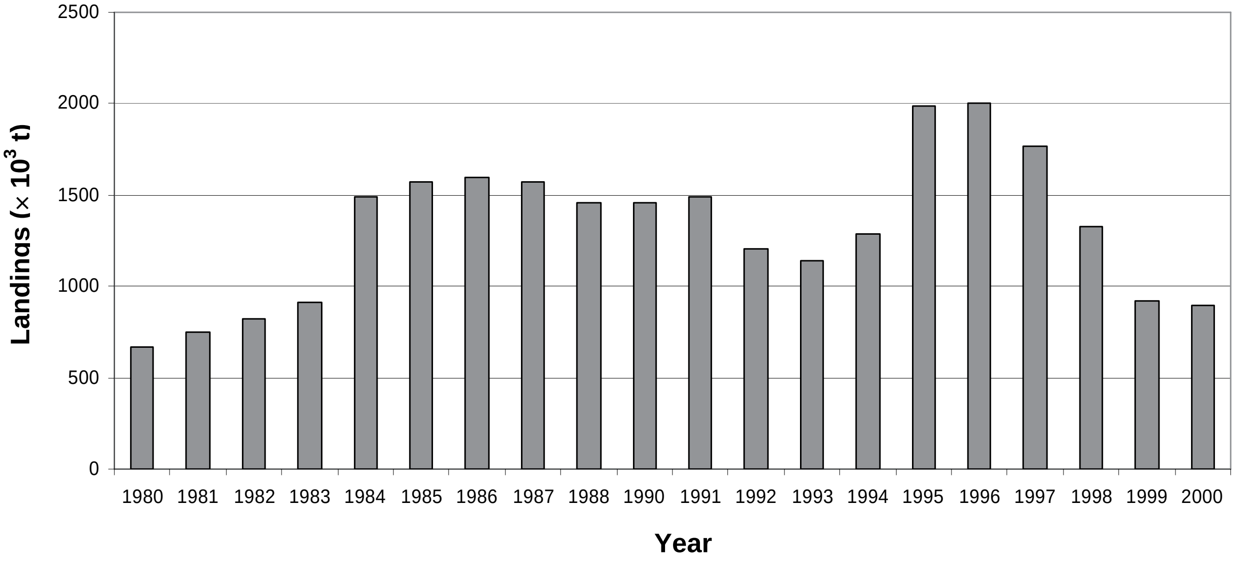

Fig. 78 Annual landings (thousands of t) of walleye pollock in the Okhotsk Sea.

food supply is better. Survival of juveniles and year class abundance also depends on how long juveniles remain under the ice cover in winter. Long periods of residence under the ice have a potentially negative impact on their survival.

Abundance and biomass the Bering Sea pollock decreased from the mid-1980s until the mid-1990s. A trend of increasing abundance and biomass of eastern Bering Sea pollock started in the late 1990s. Abundance of western Bering Sea pollock decreased significantly in the 1990s, and have remained at low levels until the present time.

The possibility of strong year classes is higher in relatively warm years, and is connected with a relatively strong inflow of the Pacific Ocean water into the Bering Sea through the Aleutian Islands passes.

Pacific herring (*Clupea pallasii*)

Biology

Pacific herring are widely distributed in the North Pacific Ocean. Their geographic range along the Asian coast stretches from the Yellow Sea in the south to the Bering Strait and southern Chukchi Sea in the north.

Within this area, Pacific herring are subdivided into several geographical groups that differ in abundance and ecology. Three main ecological forms of herring are known: off-shore (marine), coastal, and lagoon–lake. Marine herring are abundant, living entirely in oceanic water with high salinity, mainly in the shelf area. Coastal herring are usually confined to large bays and gulfs, and are less abundant. Lake herring are restricted to small bays, lagoons and lakes, where they reproduce and spend the winter, visiting neighbouring marine areas only during feeding migrations. Their biomass is low, estimated at tens or hundreds of tons.

There are four populations of marine herring in the northwestern Pacific Ocean: the Okhotsk and Gizhigin–Kamchatka stocks are distributed in the northern Okhotsk Sea, the Sakhalin–Hokkaido stock is found in the southern Okhotsk Sea and adjacent Japan Sea areas, and the Korf–Karaginsky stock lives in the Bering Sea. There are five populations of coastal herring: Korean, Peter the Great Bay, Plastun-Nelmin, and Dekastri in the Japan Sea, and Anadyr Bay in the Bering Sea. The number of local lake herring stocks is unknown. Local stocks from the bays of northeastern Sakhalin, Terpeniya and Aniva bays, as well as from lakes and lagoons of southeastern Kamchatka and Hokkaido Island are well studied. At the same time, there are almost no data on numerous small stocks inhabiting practically all brackish-water lakes and lagoons along the eastern Kamchatka coast.

Pacific herring can attain a body length of 44 cm, a body weight of 1,090 g, and can live up to 18 years, but such old individuals are rare. Most mature fish live 3 to 8 years and have a body length of 25 to 32 cm. The size and age of fish may vary, depending on ecological conditions, generation abundance and fishery pressure.

Lake herring are characterized by a short life cycle, small body size and weight, and early maturation. These fish spend the winter in brackish waters where they also spawn (bays, lagoons, and lakes that have connections with the sea). Local stocks are usually named after the lakes they spend the winter and spawn in. They do not conduct long migrations. Unlike lake herring, marine herring are larger, spawn along the shore on seaweeds such as *Zostera* and *Fucus*. They are widely distributed in shelf waters during feeding, and spend the winter on the slope (150–250 m depth), forming dense slow moving demersal aggregations.

Pacific herring are a neritic or coastal fish species, and their life cycle is associated with the shelf areas and neighbouring slope waters. Feeding migrations of herring are usually 800–900 miles (~1290–1450 km) at most.

Mature Pacific herring spend the winter in depths from 150 to 250 m, usually at temperatures from 1.5° to 3.5°C in areas 60–400 miles (~96–645 km) from the spawning regions. The most distant wintering regions are located in the wide shelf areas of the northwestern Okhotsk Sea and eastern Bering Sea. Young herring are distributed at depths from 50 to 200 m, and can be found at water temperatures less than 0°C. Pacific herring usually stay near the bottom during the day and move up the water column to the surface at night.

Some populations of Pacific herring (*e.g.*, from Peter the Great Bay) mature in their second year and at a body length of 17 to 20 cm. However, most mature at the age of 3. Sakhalin–Hokkaido herring mature in their fourth year, while Korf–Karaginsky herring mature in their fifth. Usually, it takes 3 to 4 years for the fish to mature. Males mature earlier and faster than females.

The fecundity of Pacific herring varies from 9,000 to 140,000 eggs, depending on the age and size of the fish. Herring populations from the southern areas are characterized by a high growth rate and fecundity. The average fecundity of Pacific herring from Peter the Great Bay is 72,000 eggs, in the western Hokkaido region it is 60,000 eggs, and in southwestern Sakhalin it ranges from 70,000 to 87,000 eggs. Korf–Karaginskyi herring have a fecundity of about 60,000 eggs. Population fecundity has annual variations, depending on age composition of the spawning stock, and feeding conditions.

Pacific herring feed the whole year round, though the intensity differs by season. The highest feeding activity is observed immediately after spawning. In winter, the feeding rate is low, and increases just before spawning time. Pacific herring feed mainly on copepods, eupahusiids, and chaetognaths. In the Bering Sea, they also feed on amphipods and decapod larvae. Fish (sand lance larvae, pollock eggs and larvae, juvenile herring) are extremely rare in herring stomach contents.

The spawning period of different Pacific herring populations depends on the geographical area. In Peter the Great Bay, and near the coast of Hokkaido, spawning starts in late February–early March and ends in April. Spawning continues until April in the southwestern Sakhalin area, from May–June in the Okhotsk and Bering seas, and from late June to early July in Anadyr Bay and Chukchi Sea. Spawning takes place in brackish water at a temperature range from 0° to 14°C, with an optimum temperature of 2° to 6°C and salinity of 5 to 28 psu for egg development.

Pacific herring stocks differ in their abundance. Annual and long-term trends in the dynamics of herring abundance are similar. Biomass has increased considerably since the early 1990s.

In recent years, the Okhotsk, Korf–Karaginskyi, and Gizhigin–Kamchatka populations have been highly abundant, and form the basis for the Russian herring fishery (Fig. 79, Tables 39 and 40). Other stocks are less important.

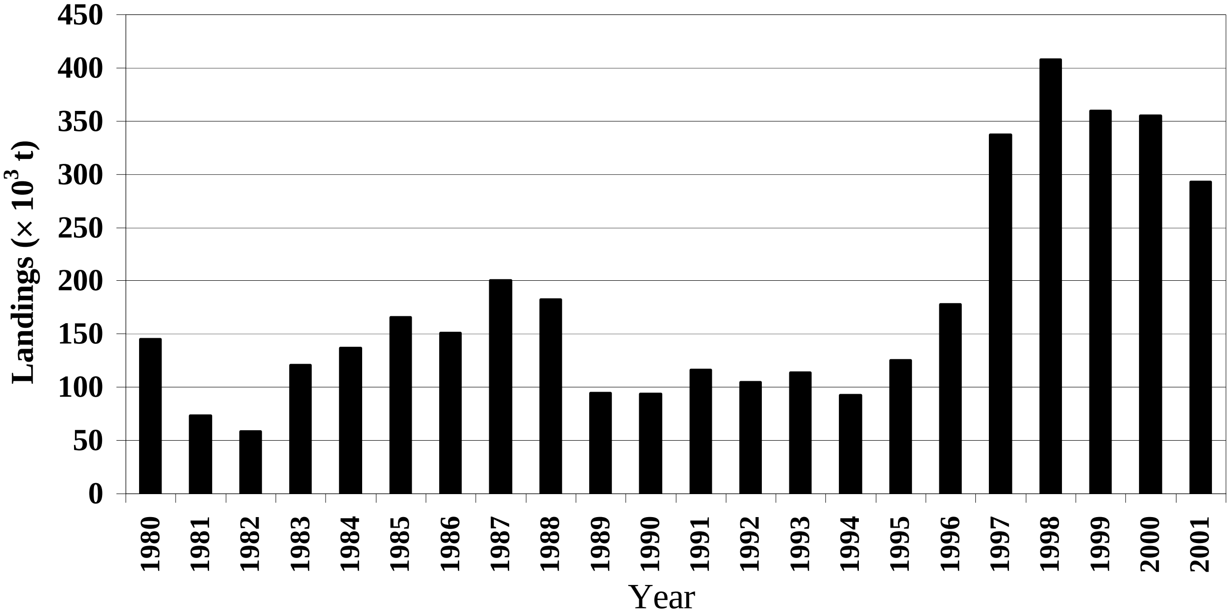

Fig. 79 Annual landings (thousands of t) of Pacific herring in the Russian Exclusive Economic Zone.

Table 39 Pacific herring catches (t) in the Russian EEZ (FAO data).

Year	Catch
1980	79,251
1981	85,552
1982	89,032
1983	132,892
1984	150,161
1985	189,584
1986	168,356
1987	220,712
1988	189,477
1989	99,966
1990	97,357
1991	98,326
1992	109,279
1993	115,148
1994	85,218
1995	116,787
1996	171,810
1997	313,397
1998	395,595
1999	359,194
2000	361,241
2001	278,511
2002	203,411

Fishery

It should be mentioned that every year herring landings are lower than the Total Allowable Catch (TAC), with annual catches not exceeding 60 to 70% of the TAC. This is because only two (Okhotsk and Korf–Karaginskyi) of the three potential populations, accounting for 95 to 97% of the TAC, are harvested commercially. Only 5 to 20% of the Gizhigin–Kamchatka herring TAC, estimated at 73,000 to 97,000 t in 1999–2001, was taken because there is no specialized fishery for this fish during its feeding period. It is harvested only in spring on the spawning grounds as a bycatch during the fishery for the Okhotsk herring stock. Gizhigin–Kamchatka herring catches may also decrease due to a decline in stock abundance, which is related to the elimination of the highly abundant 1993 year class from the commercial stock. Forecasts for stock abundance of Pacific herring have been made, taking into account the regularity in the appearance of highly abundant generations (Table 40).

Pacific saury (*Cololabis saira*)

Biology

Pacific saury, a subtropical species, occurs in the upper epipelagic layers of the North Pacific Ocean. In the offshore areas, its range is bounded by the Japanese and Kuril islands in the west, North American coast in the east, Komandor and Aleutian islands in the north, and northern subtropical convergence zone in the south. Pacific saury is common in the Japan Sea and southern Okhotsk Sea. The species occasionally occurs in the southern Bering Sea, and off western and eastern Kamchatka.

Pacific saury reproduce in the Kuroshio Current and its extension, the North Pacific Drift, and to the east in the California Current. Spawning is extended, and takes place in the South China and Japan seas. The species spawns all year round, with a peak in winter–spring in the Kuroshio, and in spring–autumn in the South China and Japan seas. Average individual fecundity is about 16,000 eggs. Eggs are released in small portions and are laid on floating algae.

As a rule, almost all eggs are fertilized. Embryonic development lasts 10 to 15 days, and survival rate is 30 to 45% by the time of hatching. The size of newly hatched larvae is about 6 mm. The larval phase ends at a body length of about 25 mm, fry phase at 60 mm, and juvenile phase at 240 mm. Most individuals spawn at body length of 29 to 30 cm. Spawning and feeding individuals have different distributional patterns. The main food items are: copepods (*Neocalanus*, *Paracalanus*), euphausiids (*Thysanoessa*), amphipods, and pteropods. Pacific saury larvae consume mainly small copepods (*Oncacea*, *Corycaeus*, *Oithona*, *Clausocalanus*, *Paracalanus*, *Calocalanus*).

The maximum length of Pacific saury is 38 cm. In commercial catches, it ranges from 10 to 34 cm, with individuals 24 to 30 cm long being the most abundant. No sexual dimorphism is observed. The Pacific saury life cycle is short and does not exceed 2 years. One-year-old (7–14 months) individuals constitute the bulk of commercial and total stock.

Table 40 Expected catch (t) of Pacific herring in the Russian Exclusive Economic Zone (EEZ) from 2000 to 2015.

Region	**2000**	**2005**	**2010**	**2015**
Western Bering Sea	52.5	30.0	45.0	60.0
Eastern Kamchatka	117.5	70.0	110.0	150.0
Okhotsk herring	260.0	410.0	325.0	120.0
Gizhigin–Kamchatka herring	87.0	80.0	90.0	110.0
Okhotsk Sea total	347.4	440.0	415.0	230.0
Japan Sea	4.2	4.0	4.5	5.0
Total	521.6	594.0	574.5	445.0

Fishery

Pacific saury catches increased through the 1980s, reaching a maximum in 1990 (Table 41). Catches declined to very low levels in the mid-1990s, with the lowest levels since 1980 occurring in 1998 and 1999. Beginning in 2000, they increased and current catches are similar to those of the early 1990s.

Table 41 Pacific saury catches (t) in the Russain EEZ (FAO data).

Year	**Catch**
1980	38,600
1981	31,700
1982	26,293
1983	7,606
1984	30,447
1985	23,423
1986	24,902
1987	23,484
1988	50,927
1989	68,368
1990	72,618
1991	49,943
1992	50,172
1993	48,145
1994	26,385
1995	25,140
1996	10,280
1997	7,091
1998	4,665
1999	4,808
2000	17,390
2001	40,407
2002	51,709

Climate and ocean effects

Pacific saury abundance depends primarily on the conditions within spawning areas, and on survival at early ontogenetic stages. In the ocean, 19-year-long natural cycles of Pacific saury high abundance were observed, related to the tidal rhythm of the moon. Lunar activity affects the position of frontal zones, processes of meandering, and the formation of eddies. The Kuroshio path is considered to be of primary importance for the reproduction of pelagic fishes in the northwestern Pacific Ocean. Southward shifts of the current position normally lead to enhanced yields of fish generations, while stock abundance decreases in years when the flow approaches the coast.

A rise of Pacific saury abundance in the Japan Sea is observed during periods of warm winters. This is related to the increase in non-predatory plankton biomass, matching with the production of the saury larvae. The decrease in food competition between Pacific saury and other pelagic fish is another factor for the increase in saury abundance.

In both the Pacific Ocean and Japan Sea, the increase in Pacific saury abundance occurs during intensification of the Kuroshio, and is related to the extent of water warming. In the Pacific Ocean, an intensive meandering of the stream is a necessary condition favouring the increase in abundance.

Pacific sardine (*Sardinops sagax*)

Biology

In winter–spring (December to May), mature Pacific sardines are concentrated in the coastal area of Japan where they spend winter and spawn. Small immature sardines are concentrated in the subarctic frontal zone. Beginning in April, just after spawning, the fish migrate to feeding areas in the northern Japan Sea. Feeding migrations end at different times, depending on the length of spawning periods, and abundance. At low abundance, the last schools of sardine approach Primorye and Sakhalin in late June. At high abundance, the time of migration is prolonged until mid-June, and in this case, small first maturing fish are the last to appear in the region. In September, after a period of growth, sardines start migrating back to the southern areas. Fall cooling of surface layers in the feeding areas, resulting from warm water moving off the shallow shelf zone, promotes the beginning of sardine migration to their spawning regions. By late October –early November, almost all schools of sardine move away from the coasts of Primorye and Sakhalin. In December, sardines are distributed in the Japan Sea only along the western coast of the Japan. Across their wide distributional range, sardines are found in large numbers at water temperatures of 8° to 25°C.

Pacific sardines mature at the age of 3+ and body length of 17 to 19 cm. By the age of 4, 99% of the fish are mature (Ishigaki *et al.*, 1959; Ito, 1961).

Individual fecundity varies from 39,900 to 318,800 eggs. Gonad maturation begins in November, gaining intensity from December to February. Spawning occurs from March until May. By the beginning of spawning, the majority of females have two generations of oocytes which are later released in two pools during one spawning period. Sardines release from 24,000 to 27,000 hydrated eggs into the surface layer during a single spawning event. Eggs are pelagic, free-swimming, with an adipose capsule. Embryonic development lasts 35 to 85 h, depending on water temperature. Sardines spawn at 14° to 17°C, with a mass spawning at 15.5°C.

Fishery

Catches increased through the 1980s, reaching a maximum in 1989 and 1990 (Table 42). They started to decline in 1991 and by 1995, there was no catch. Virtually no sardines have been caught since 1994.

Climate and ocean effects

Pacific sardines are characterized by a relatively short life span. In the Japan Sea, five to seven age groups are found. In the 1980s, the most numerous were fish aged 3+, accounting for 62 to 79% of the total catch (Dudarev, 1985). The sex ratio for Pacific sardine caught in the Japan Sea is 1:1.

Five large rapid rises in sardine abundance were reported during the last 500 years. They were observed during periods of low solar activity. These periods are accompanied by climate warming, favourable for an increase in sardine abundance. Shuntov (1982) considered that favourable conditions for sardine reproduction were related to a zonal type of atmospheric circulation. The late 1980s proved this hypothesis. During that period, zonal (westerly winds) processes prevailed over meridional (north–south) processes in the atmosphere.

Two periods of high sardine abundance occurred in the last century: one in the 1920s and 1930s and one 1970s and 1980s. Temperature and hydrological conditions were suitable for the high rates of young fish survival. It is known that favourable conditions within the entire ecosystem are essential for a rapid increase in sardine abundance. Observed variability

Table 42 Pacific sardine catches (t) in the Russain EEZ (FAO data).

Year	Catch
1980	359,289
1981	461,000
1982	594,151
1983	579,914
1984	798,764
1985	748,158
1986	820,798
1987	764,687
1988	794,641
1989	861,401
1990	879,393
1991	655,772
1992	165,270
1993	4,314
1994	28
1995	0
1996	0
1997	0
1998	0
1999	3
2000	0
2001	0
2002	0

in sardine abundance on the northern and southern spawning grounds was associated with favourable warm conditions for reproduction. In this regard, Shuntov (1982) and Davydov (1986) were correct in predicting that a 22-year cycle of solar activity, resulting in a relatively warm period, would last until the early 1990s.

At present, it is difficult to forecast the next rapid rise in Pacific sardine abundance. We suggest that, considering the duration of high and low sardine abundance periods, the state of the environment, and that sardine demographic cycles are species specific, a highly abundant generation of Pacific sardine should be expected in the second decade of the 21st century.

Pacific cod (*Gadus macrocephalus*)

Biology

Pacific cod are widely distributed in the North Pacific Ocean. Their natural habitat stretches from the Yellow Sea through the Japan Sea, the Okhotsk Sea, the northern part of the Bering Sea, and along the coast of North America to Santa Monica Bay, California. The bathymetric distribution of Pacific cod is 10 to 50 m, where the young fish concentrate. Maximum depths are up to 800 m. Mature fish live mainly at depths from 30 to 300–400 m.

As a rule, Pacific cod are not subject to vast migrations in the Russian EEZ. The majority of fish dwell in definite local regions, primarily moving from deeper depths to shallower areas and back during some seasons. The main commercial aggregation of Pacific cod in the northern part of the Bering Sea in Karaginsky and Olyutorsky bays are found above the continental shelf during summer–fall and above the shelf edge and continental slope in winter (Karpenko and Balykin, 2006).

Pacific cod are noted for their large size among the ground fishes of the Far Eastern seas. In the Japan Sea, most fish range from 45 to 75 cm in length. In the Okhotsk Sea, along the western Kamchatka coast, the species range from 45 to 80 cm in length. On the eastern side, the main group of fish ranges from 55 to 90 cm in size. In the western Bering Sea, they range from 55 to 95 cm in length. Males mature at 4 to 5 years and females mature at 5 to 6 years. The sex ratio of mature Pacific cod is 1:1, although males are smaller than females. Most fish larger than 80 cm are females. Large abundance is one of the characteristic features of Pacific cod. Biomass varies from 700,000 to 7,200,000 spawners.

The spawning period and location are connected to water temperature. During spawning, Pacific cod avoid regions that have warm near-bottom water temperatures > 10°C, as well as cold ones. In the Okhotsk and Bering seas, spawning occurs at water temperatures from 1° to 2°–2.5°C and at depths of 150 to 400 m from February to April (the peak is primarily in March). Pacific cod spawn small eggs, 1.25–1.3 mm in diameter, on the bottom. There is no adipose capsule in spawn, so its weight is greater than the water and the eggs sink immediately to the bottom. The incubation period lasts not more than 20 days, depending on the water temperature. The larvae are not larger than 3.7 mm and remain near the bottom at the site of spawning. When the young fish grow to 20 mm they migrate to the coastal area where the temperature reaches up to 15°C. Here, they grow from 40–80 mm in length and then move to deeper water.

Unlike the majority of the groundfishes, Pacific cod are characterized by great fluctuations in year class, which has an impact on catches. Warm advection of Bering Sea water, due to the warm Pacific water, influences the dynamics of the Anadir–Navarin and eastern Bering Sea cod year class.

According to Vershinin (1987), the eastern Navarin cod quantity is inversely proportional to the ice cover in the Bering Sea. In this case, ice cover is an index of water enthalpy during the spawning period. Actually, the majority of large- and average-yield generations appeared in quite hot years, and were not numerous in cold years. However, this relationship occurred only up to the end of 1970. In the 1980s, large and small year classes appeared despite the large water enthalpy. Hence, there are other factors besides the environment that play an important role in year class formation.

Fishery

Pacific cod have always made up the largest part of groundfish catches in the Russian EEZ. In the 1980s, catches of this species were 23,000 t, reaching a maximum of about 175,000 t in 1987 (Table 43). The largest catches were on the shelves of western and eastern Kamchatka, and in the western Bering Sea.

Table 43 Pacific cod catches (t) in the Russain EEZ (FAO data).

Year	Catch
1980	23346
1981	40997
1982	80016
1983	88600
1984	140523
1985	188443
1986	168445
1987	175271
1988	148397
1989	140365
1990	121397
1991	106519
1992	154297
1993	95823
1994	81445
1995	100730
1996	93890
1997	79927
1998	94282
1999	101929
2000	68415
2001	59783
2002	60625

Red king crab (*Paralithodes camtschaticus*)

Biology

Red king crabs are distributed along the North Pacific Ocean rim. There are two populations in the Okhotsk Sea, one in western Kamchatka and one in the Ayan–Shantarsk area. Populations with low abundance are found in the northern Japan Sea, off Sakhalin, eastern Kamchatka, and along the Kuril Islands. Within the Russian EEZ, the western Kamchatka population is the most abundant.

Productivity of red king crab populations depends on a generation yield, growth rate, temperature, size of shelf area, food availability, and natural and fishery mortality (Rodin, 1985). Red king crab migrate seasonally into the shelf areas in the spring through fall. Crabs spend the winter in the offshore areas at depths of 110 to 200 m because of low temperatures in the shallow coastal areas.

In spring, when the near-bottom temperature falls below zero in places where red king crabs spend the winter, mature crabs begin their migration to the coastal zone to spawn. On their way to the spawning grounds, they pass through a cold-water area where temperatures sometimes fall to –1.2°C. When warm patches with a water temperature of up to +4°C appear in those areas, they move within these warm cores. Males and females migrate separately. Every migratory crab pool has its own regional pattern (Levin, 2001). A month after the migration starts, males join females in warmer coastal regions with temperatures of 2° to 4°C. Males become mature at a carapace width of 10 to 12 cm. Carapaces of large males can reach 25 to 28 cm in width. The smallest females with eggs have a carapace width of 8 cm. Most females with a 9 cm carapace width are mature and carry eggs.

Individual fecundity of females during maturation depends on conditions such as food and hydrological regime (Rodin, 1967). Annual egg production may vary within a female. Females carrying different numbers of eggs were observed by Sato (1958). This author found groups of females with a carapace width up to 15.6 cm having as many as 75,000, 150,000 and 200,000 eggs per female. The number of eggs is positively correlated with size. On the western Kamchatka shelf, red king crab fecundity increases from the north to the south. During years with moderate temperatures, individual fecundity for all size groups increases by 4,000 to 25,000 eggs. Females keep up to 300,000 fertilized eggs for 11.5 months. On the third month of egg care, a new portion of eggs appear in the female’s ovaries.

Larvae hatch at 24 to 40 m depth from April to May. On the eastern Kamchatka shelf they are transported north of the spawning sites. Larvae with different stages of development present different distributional patterns by depth and along the coastline. Larvae, hatched near the shore, migrate to deeper areas as they grow. They settle on the bottom in August. The largest aggregations of the crab larvae and juveniles are found within the coastal zone.

Red king crabs feed mainly upon mollusks, as well as on different crustacean species and polychaetes. They also regularly prey upon echinoderms, sponges, rhizopods, bryozoans, and hydrants, such as *Obelia* (Logvinovich, 1945; Kun and Mikulich, 1954; Nadtochij *et al.*, 1998).

Fishery

The most complete information about red king crab landings in the western Kamchatka area was collected during its intensive harvest from 1924 to 1983 (Slizkin *et al.*, 2001). In the last decade, the annual catch was less than half of the maximum annual catch.

Eight relatively high-yielding generations have been recruited into the western Kamchatka red king crab population during the last 40 years of observations (Fig. 80). These generations appeared every 4 to 7 years. In 1993–1994, two high-yielding generations appeared, one after the other. These generations were recruited into the fishery stock and were harvested in the 1990s until 2000. Currently, a decline in crab abundance is expected due to the lack of high-yielding generations.

Climate and ocean effects

The study of mechanisms affecting productivity shows that during cold years, when crab migrations to the coastal zone are delayed, females begin spawning in the outer shelf areas. Larvae from those females that cannot pass through the cold water belt below –1°C, hatch at depths from 80 to 120 m. In these cases, severe conditions, as well as larval drift to the regions with unfavourable conditions for settling (for example, outside the western Kamchatka shelf), usually result in higher larval mortality than in the moderate and warm years. Thus, generations appearing in cold years are relatively low-yielding. In warmer years, larvae hatch in coastal waters, and as a result, they aggregate within a 30 to 50 m depth where they are successfully transported into eastern Shelikhov Bay, which is favourable for their growth. Strong year classes appeared in 1958, 1963, 1970, and 1971.

In the 1980s and 1990s, only two strong year classes of red king crab were observed in the western Kamchatka shelf (Slizkin *et al.*, 2001). During 1996–1998, an abnormally low number of males and non-migrating juveniles were observed. In the late 1990s, the most numerous groups were recruits and pre-recruits (males with a carapace width of 1.1 to 14.5 cm). They were able to effectively replenish the commercial part of the stock only until 2001. In future years, a decrease in the number of males recruiting into the harvested stock (with a carapace larger than 15 cm) will result in a stock decline.

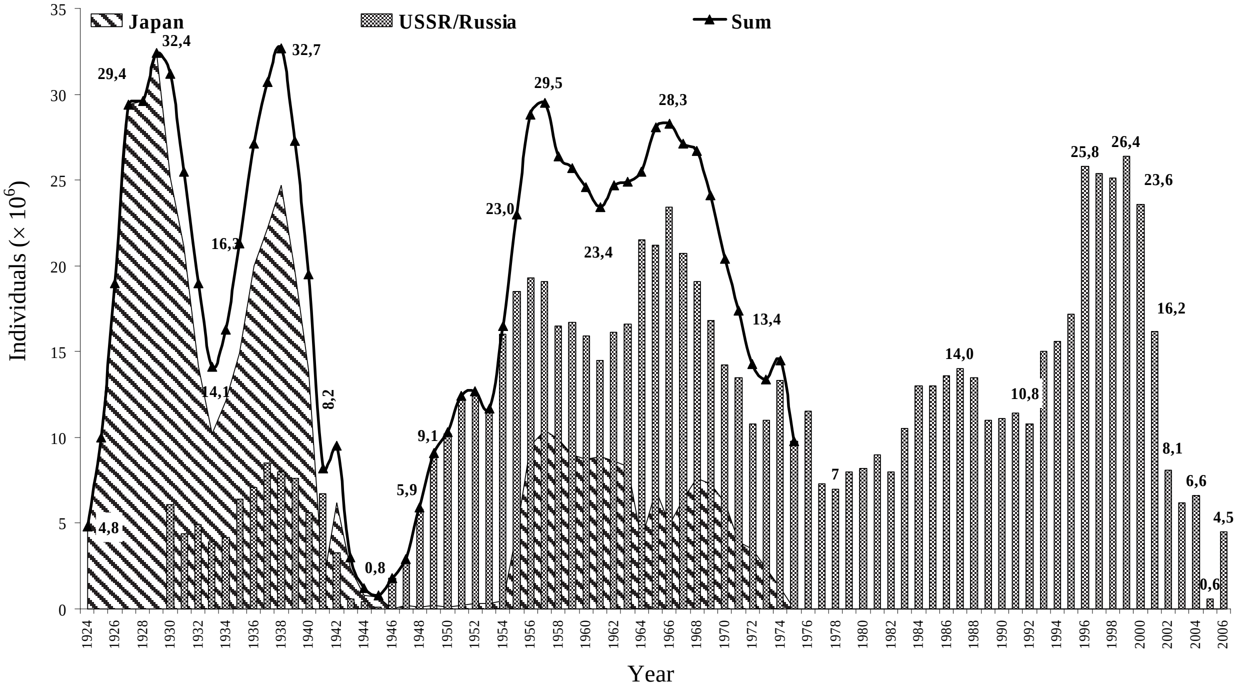

Fig. 80 Annual landings of red king crab in the Russian Exclusive Economic Zone (EEZ) (Slizkin and Safronov, 2000), with modifications.

In the 1990s, an unusual behaviour of crabs was observed when over half of all males and a notable number of females were found in nontraditional spawning areas (Slizkin *et al.*, 2001). This resulted in an increased catch of females and non-commercial sized males. Long-term environmental changes, together with high fishing pressure, were the basic reasons for the unusual spatial distribution pattern of the crabs with their aggregation south of 54°N.

An analysis of oceanographic conditions showed that in 1998, western Kamchatka coastal near-bottom water (15–100 m deep) was cold relative to the annual average, while in the outer shelf area (130– 200 m and deeper), the water was relatively warm. Unlike previous years, the cold compensatory current in 1998 prevented the western Kamchatka coastal area from access to the West Kamchatka Current warm water. As a result, water temperature near the bottom in the coastal area was 2° to 4°C lower than in 1997.

In the spring and summer of 1998, abnormal oceanographic conditions in the coastal reproductive and breeding shelf areas appeared as a result of the development and persistence of a cold counter-current. These unusual environmental conditions caused a number of changes in the distribution and biology of bottom organisms. Permanent cooling of the near-bottom water layer along the western Kamchatka coast resulted in a red king crab migration from the Hairuzovo to Ichin regions in the shelf, which, in turn, led to a sharp decline in their abundance in the northernmost areas.

Climate, Ocean and Fishing Effects on Key Species in the Fishery

An important question to consider is whether the productivity of a stock is affected by common factors, which also control the synchronous fluctuations of the principal climatic, geophysical and biological indices.

In the late 1980s, the annual commercial catch in the Pacific was close to 54 million t. The total catch of the five main Pacific commercial species (Japanese and Peruvian sardine, Alaska pollock (also referred to as walleye pollock), Chilean jack mackerel, and Peruvian anchovy) made up 52% of this total (28 million t).

Major species in the commercial catch off the east coast of Russia can be placed in two groups. Group I includes Pacific salmon, walleye pollock and Japanese sardine. Group II includes Pacific herring. The maximum catch of species in Group I occurred in the late 1930s and early 1990s, with the minimum catch in the 1960s. The maximum catch for Group II fish occurred in the 1960s, with minimum catches in the 1930s and 1990s.

The population dynamics of fish in the first group corresponds to the global trend in surface temperatures and to large-scale climate indices in the Pacific, such as the Pacific Decadal Oscillation (PDO) and Aleutian Low Pressure Index (ALPI). The PDO characterizes an area of low pressure in the North Pacific and is considered a basic climate-forming factor of the region. Group I fishes can be conditionally considered to be “warm-watered” because the increases in catch coincide with periods of global temperature rise, and with periods of prevailing “zonal” Atmospheric Circulation Index (ACI), positive PDO, and intense ALPI. The fluctuation of catches, PDO, and ALPI has an approximately a 60-year periodicity (Fig. 81).

Group II fishes can be conditionally described as “cold-watered” because periods of increased catch coincide with lower global temperatures and with periods of “meridian” ACI domination, negative PDO, and weak Aleutian Lows.

The concept of an approximately 60-year periodicity of fluctuations in climate and catches is based on a relatively short time series (100–150 years) analysis, and an even shorter time series of catches. Time series with a length of hundreds, and even thousands, of years are necessary in order to be clear about the periodicity in climate changes.

We propose that the modern fluctuations of climate and fish productivity will continue to follow 50- to 60-year cycles. According to the model production, catches of the so-called “warm-watered” or the zonal group of fishes, such as Pacific salmon, walleye pollock, Japanese sardine and others will decrease to about 2020. After 2020, production will begin to increase (Fig. 82). Catches of the so-called “cold-watered” fishes, or the meridian group, such as Pacific herring, will increase up to 2020 and then decrease.

Klyashtorin and Lyubushin (2007) show that the increasing trend of global temperatures may change, resulting in a declining trend until 2020.

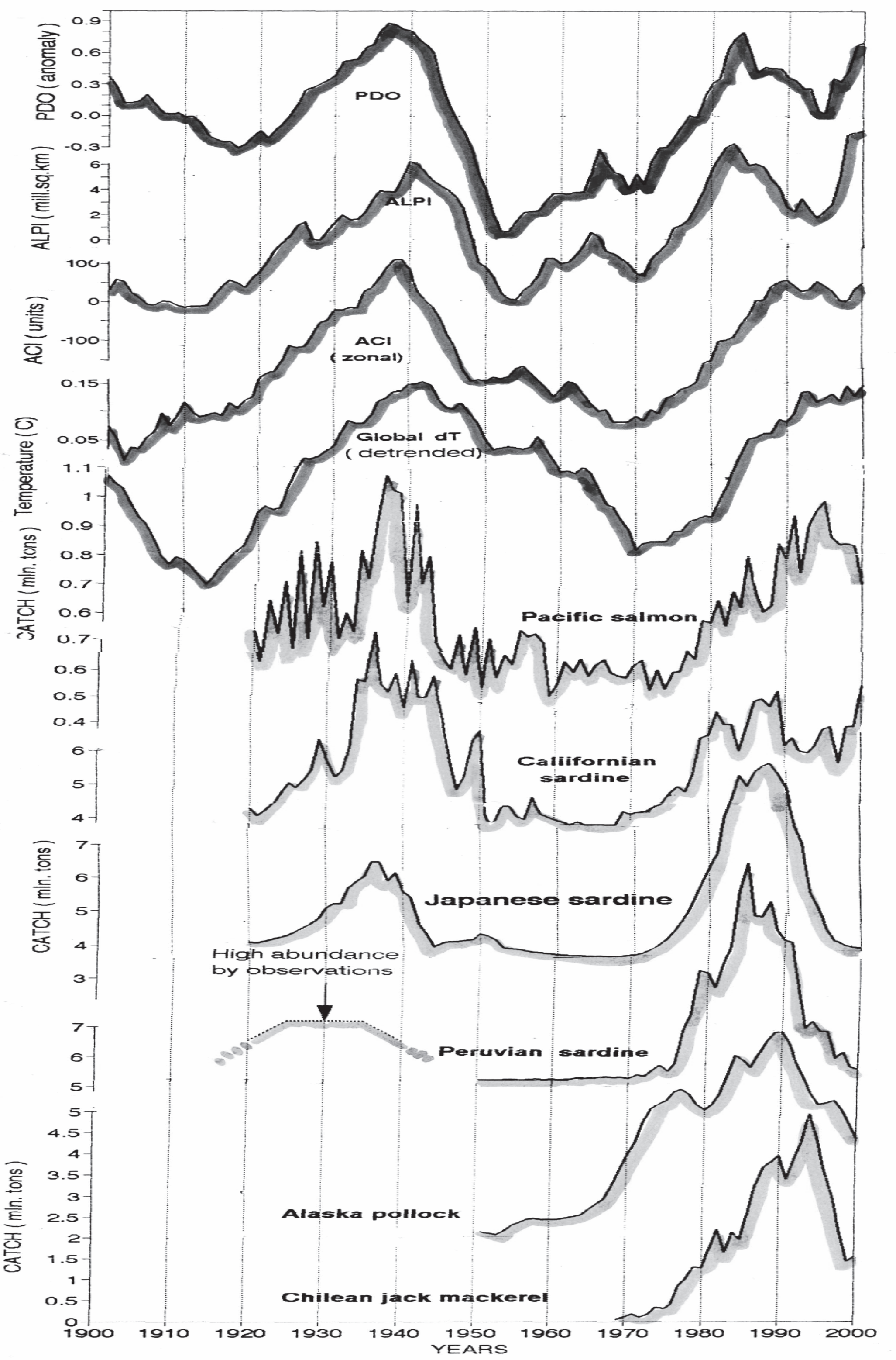

Fig. 81 Coherency of climate and commercial catch dynamics in the Pacific from 1900 to 2000.

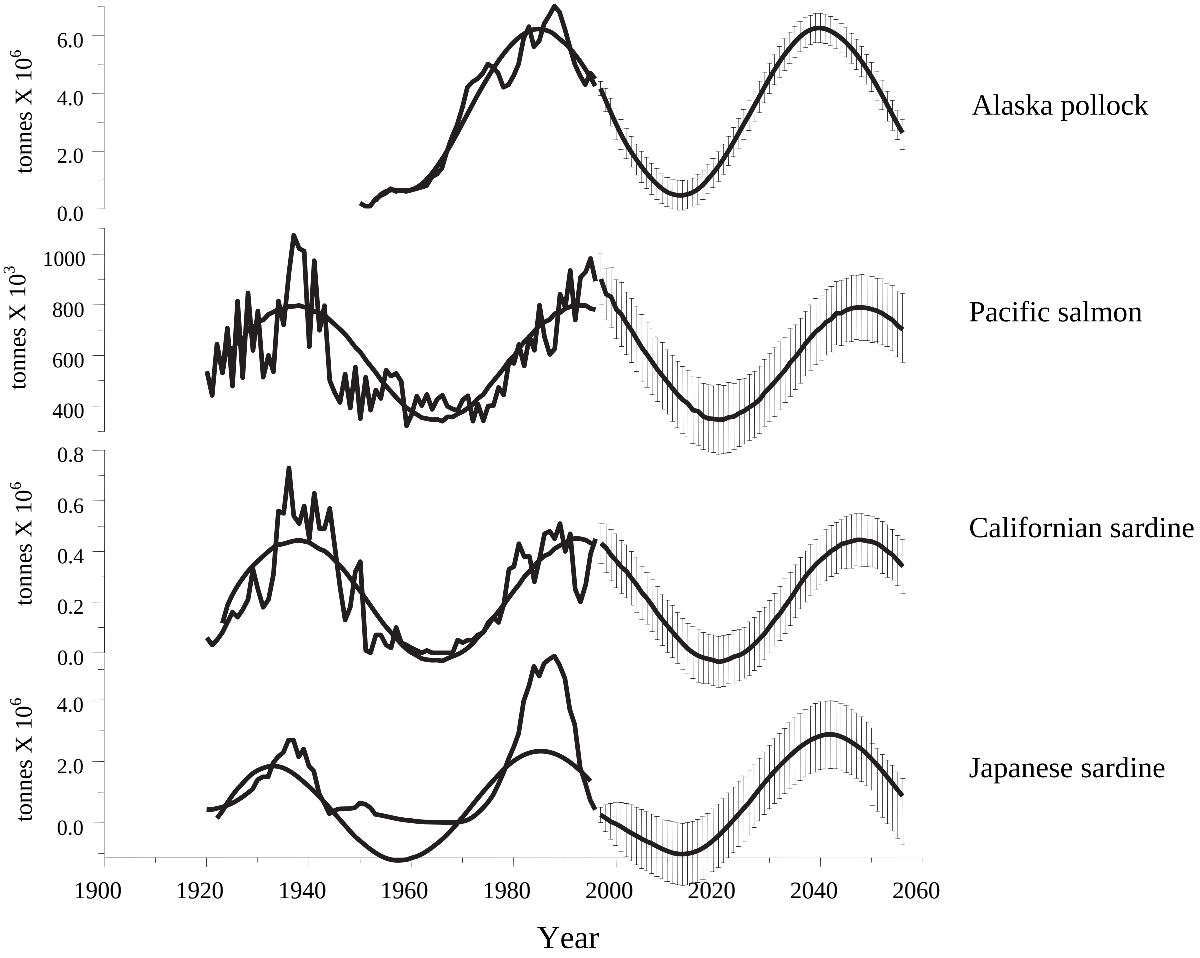

Fig. 82 Model-generated dynamics of "zonal-dependent" (thermophilic group) stocks of major commercial species for 2000 to the 2050s.

Future Responses

The processes that regulate yield are very complicated and are governed by many factors, with climate and oceanographic influences being important. Numerous factors influencing the abundance of generations and populations can be classified as follows: (1) cosmophysical and global climate–oceanic factors, which form long-term periods and epochs; (2) climate and hydrological conditions of a particular year and region; (3) biocenological relations, connected with the density factor (through food competition); (4) predation at different ontogenetic stages; (5) population factors, including those with auto-control; and (6) anthropogenic impact on the biota and environment, including fisheries and aquaculture. Theoretically, it is very difficult to forecast trends in the dynamics of marine organism abundance because potential factors are numerous, and it is hard to assess possible impacts and variability within an ecosystem. That is why regular annual monitoring plays an important role in forecasting for a commercial fishery.

The current low level of catch in the Far Eastern seas fisheries was forecasted (Shuntov, 1986). This period will last for two decades according to the 40- to 60-year cycles in climate and the ocean environment, and the associated variability in the biological structure of ecosystems.

As for the global warming idea, at the present time there are no serious grounds to consider it the first priority problem, at least, in the next few decades. Besides, the frontier of the 20th and 21st centuries was unusually cold in the Far Eastern seas. According to long-term climate variability, the 21st century is going to be warmer than the 20th century. Such a scenario will favour biological productivity in the sense that biological and fish production will increase in the new century. Presently, it is the relatively cold and severe environmental conditions that serve to limit fish productivity in the Far Eastern seas.

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Introduction

The Earth's atmosphere is warming. Air temperatures had generally fluctuated over a fraction of one degree for centuries, until the 20th century when a prominent accelerated rise in air temperature was observed (Fig. 83). This rise was 1°C over the past 142 years in the northern hemisphere. Temperature stabilized or slightly declined from 1940 to the late 1970s, and continued to accelerate from the late 1970s (Fig. 84). This rising atmospheric temperature trend from the 1970s is expected to change the global marine environment in the immediate future. The reasons for the atmospheric temperature increase are many, but greenhouse gas effects from carbon dioxide accumulations in the atmosphere have been recognized as one of the major causes (Fig. 85, IPCC 2001).

As the atmosphere warms, a large part of the world's oceans warm, too (Levitus *et al.*, 2000). The world's oceans went through two distinct warming periods during the past 100 years (Fig. 86). The first period of warming occurred from 1920 to 1940 (not shown in the figure) and was followed by a period of cooling; the second warming period began during the 1970s. The heat content of the world's oceans increased by about 2 × 10^{22} joules between the mid-1950s and mid-1990s, representing a volume mean warming of 0.06°C (Levitus *et al.* 2000). The top 300 m layer warmed 0.31°C while the top 3,000 m

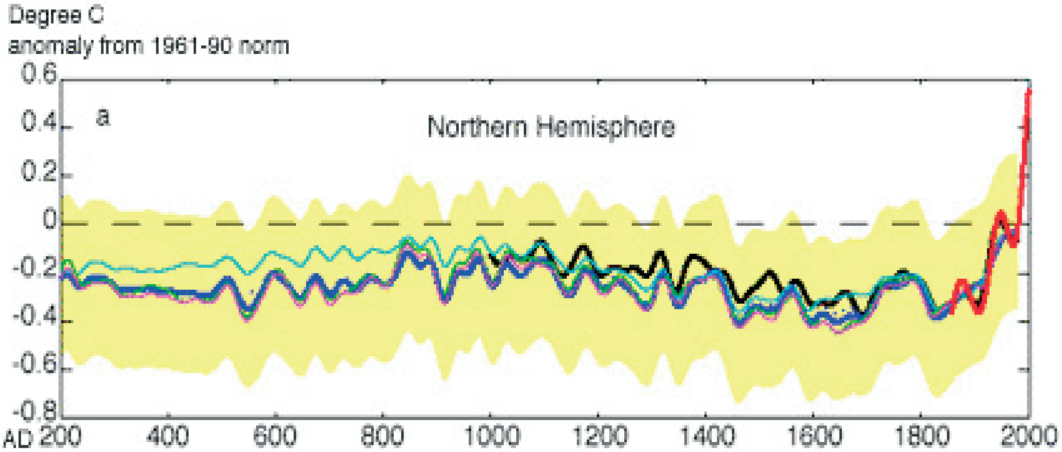

Fig. 83 Long-term trend of the Earth's air temperature, AD 200–2000, from proxy temperature indicators and direct measurement (red) (from Mann and Jones 2003).

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[1] This report is a coordinated compilation of many reports written by subject experts on the potential impacts of ocean warming and associated environmental changes on some key fisheries resources in the Alaska Region. Thus, this report reflects the views of many authors as opposed to those of the coordinator.

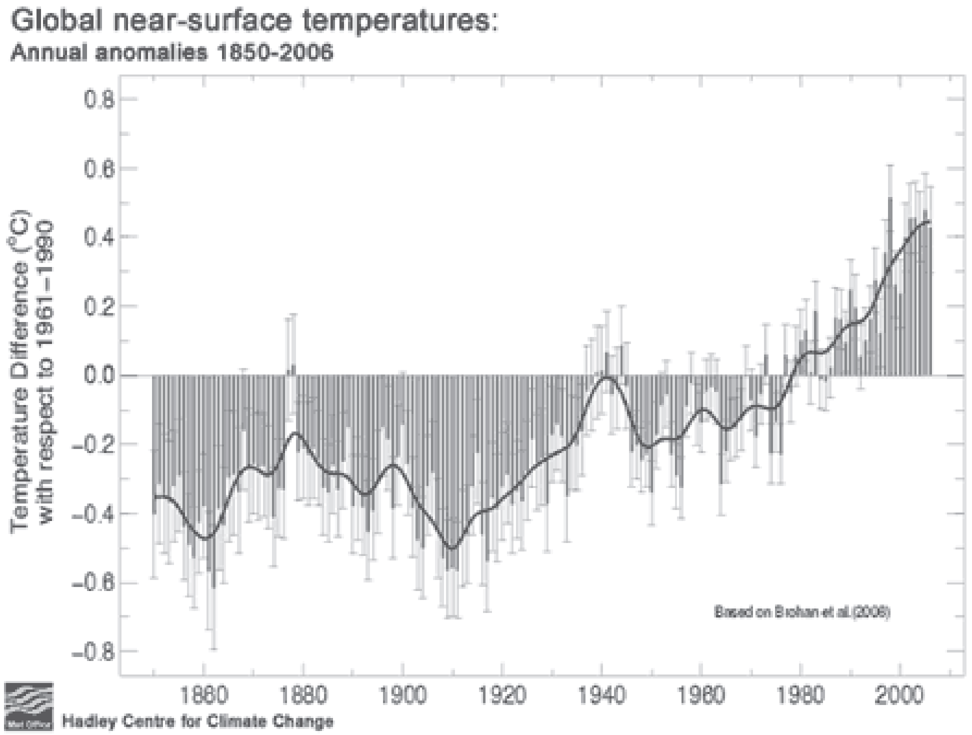

Fig. 84 Global near-surface temperatures, 1850–2006 (difference from 1961–1990 in °C). Bars represent the global temperature for each year. The solid line is the 10-year running average (figure taken from http://www.metoffice.gov.uk/research/hadleycentre/ar4/wg1report.html).

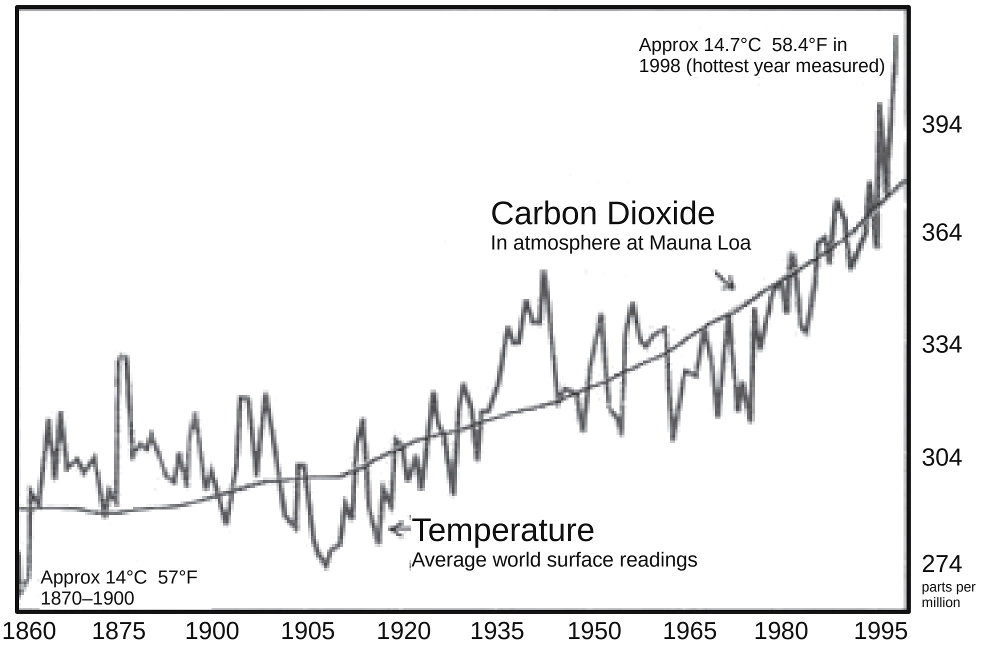

Fig. 85 Sharp rise in global temperatures since the 1850s, thought to be caused by a steep increase in atmospheric carbon dioxide, CO_2, from human use of fossil fuels. Surface temperature from 1860 to 2001 shows the rise has been uneven, but steep, while atmospheric CO_2 has risen steadily to above 370 parts per million, the highest level in more than 420,000 years (from IPCC, 2001).

layer warmed by 0.06°C. Levitus *et al.* (2000) explained that the accumulation of heat content was due to a combination of human-induced effects of atmospheric warming and other natural effects in the deep oceans. Up in the water column where many fish live, the main effects of warming in the past 50 years is due mainly to increased intensity of atmospheric circulation patterns.

Another natural effect of warming, though minor by comparison to atmospheric temperature, is underwater volcanic activities. They are known to be actively contributing some heat to the oceans, but mainly in the deep oceans, and especially around the "Pacific Rim Ring of Fire" region. Even under the Arctic Ocean, there is more hydrothermal activity than previously realized. This activity was discovered by researchers aboard two icebreakers, the USCGC *Healy* and the German PFS *Polarstern*, in an international expedition in the Arctic in 2001, known as AMORE (Arctic Mid Ocean Ridge Expedition). The scientists found surprisingly strong magmatic activity over the Gakkel Ridge, a gigantic volcanic mountain chain stretching beneath the Arctic Ocean (Edmonds *et al.*, 2003). Hydrothermal hot springs on the seafloor were far more abundant than first predicted.

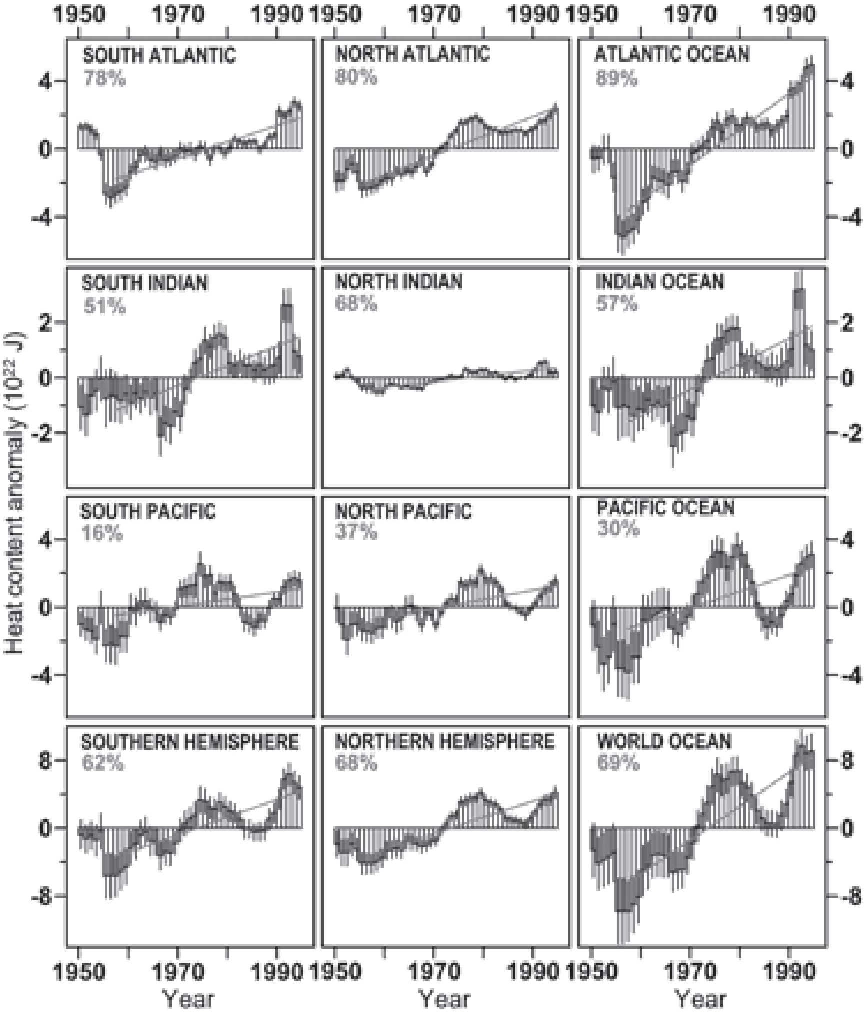

Fig. 86 Time series of 5-year running composites of heat content (10^{22} joules) in the upper 3000 m of each major ocean basin. Vertical lines represent plus or minus 1 standard error of the 5-year mean estimate of heat content. The linear trend is estimated for each time series for the period 1950 to 1996 (from Levitus *et al.*, 2000).

The ocean and atmosphere interact together in complex ways to produce what we know as climate. Owing to its large mass, the ocean acts as the "memory" of the Earth's climate system and can store heat for long periods of time – for decades or even longer. As the water temperatures rise and atmospheric forces change, the ocean environment and its ecological processes are expected to change, thus affecting living marine resources (LMRs). While some of the features of these changes can be determined, for the most part, they are still unpredictable. This is particularly true when relating climate to ecosystem structure, since physical–biological coupling is non-linear, and the biological response is an integrated process of many physical signals from a number of time and space scales and sources. In addition, the impacts of higher temperatures on LMRs would get "integrated" into the impacts of other environmental changes and events that simultaneously take place in the oceans. The effects of climate change are expected to vary from species to species and within different ecosystem settings. While changes are likely to occur for all the species, the purpose of this report is to pick key species groups that will illustrate the effects of some potential changes to Alaskan ecosystems.

The species groups addressed in this report are among the more important commercially harvested species off Alaska: Pacific salmon, Pacific herring, dominant groundfish species, flatfish, crabs, and shrimps. These species generally account for more than 95% of all commercially harvested fisheries off Alaska and about 50% of all catches for the entire United States (NMFS, 1999). Since this report focuses on fisheries resources, the potential impacts of climate change to the lower trophic level organisms, and apex predators, such as marine mammals and seabirds, are not addressed. Climate changes that affect these resources can have indirect impacts on fish through bottom-up or top-down forcing.

Large Marine Ecosystems off Alaska

Three large marine ecosystems are relevant to this report: the Gulf of Alaska (GOA), the Bering Sea–Aleutian Islands (BSAI), and the Arctic ecosystems (Fig. 87). The GOA is exposed to the ocean environment of the central North Pacific Ocean. The dominant circulation in the GOA is characterized by the cyclonic flow of the Alaska Gyre (Fig. 88). The circulation consists of the eastward-flowing Subarctic Current System at about 50°N and the Alaska Current System. The Alaskan Stream and the nearshore Alaska Coastal Current flow westward along the northern GOA. Large seasonal variations in freshwater input and wind-stress curl in the GOA affect current speeds, meanders of the Alaskan Stream, and eddies of nearshore areas. It is the variations in these flows and eddies at the nearshore environment that affects a large part of the biological variability of the region.

The Bering Sea is a semi-enclosed high-latitude sea. It has a broad continental shelf that is one of the most biologically productive areas in the world. A special feature of the Bering Sea is ice coverage over most of its eastern and northern continental shelf during winter and spring. A dominant ocean circulation feature is the passage of North Pacific water (the Alaskan Stream) into the Bering Sea through the major passes in the Aleutian Islands (Fig. 88). There is net water transport eastward along the north side of the Aleutian chain, and northward at the continental shelf break and at the eastern perimeter of Bristol Bay. Bering Sea water eventually exits northward through the Bering Strait, or westward and south along the Russian coast, entering the western North Pacific via the Kamchatka Strait.

The Arctic region is the farthest north and the least understood of the three large Alaska marine ecosystems. It is part of the Arctic Ocean which lies almost entirely above the Arctic Circle (66.7°N). It is nearly surrounded by land, and its outlets are the Bering Strait between Alaska and Russia, Davis Strait between Greenland and Canada, and Denmark Strait and the Norwegian Sea between Greenland and Europe. The Arctic Ocean is ice bound most times of the year. Water movement in the Arctic Ocean is dominated by the East Greenland Current. This current is strong due to the number of rivers that flow into the Arctic Ocean. The main outflows of Arctic waters run through Smith Sound, Baffin Bay and Bering Strait. There is also a circular current in the Arctic Basin which is created by water deflecting off northern Greenland.

Since so much less is known about the Arctic ecosystem, we have focused on the Gulf of Alaska and the Bering Sea ecosystems. Yet, the Arctic region is where the greatest changes would be expected to take place as ocean and air temperatures continue to increase. Because of this gap in our knowledge, we support continued research on the Arctic ecosystem.

Fig. 87 The three major marine ecosystems off Alaska: the Gulf of Alaska (the western boundary is 170°W longitude), the Bering Sea–Aleutian Islands (BSAI), and the Arctic Ocean. The Large Marine Ecosystems (LMEs) are bounded by the 200-nautical mile outline of the U.S. Exclusive Economic Zone. The boundaries between the LMEs are, in reality, fuzzy. Generally, the Bering Strait separates the Chukchi and Bering Sea LMEs and the 170°W longitude (below the Aleutians) separates the Bering Sea and Gulf of Alaska LMEs.

Environmental Regimes

The North Pacific Ocean has experienced different climatic regimes and shifts in modern times. Regime shifts imply changes in the characteristic behavior of the physical environment. These shifts could be caused by a combination of factors, but a persistent increase in ocean and atmospheric temperatures is the important factor, as well as shorter-term perturbations related to climatic events. A basin-wide shift in climate regimes in the North Pacific appears to have resulted from changes in atmospheric forcing which strongly affect sea surface temperatures. There are two principal modes of remotely forced sea surface temperature anomalies acting in the North Pacific Ocean, the shorter-term El Niño–Southern Oscillation (ENSO) events and the longer-term Pacific Decadal Oscillation (PDO) events (Mantua *et al.* 1997).

The question posed by the United States to PICES of whether the North Pacific marine environment has shifted to a different state or regime since the late 1980s resulted in a publication by King (2005). The report indicates that the environment of the North Pacific marine ecosystems has apparently shifted a few times. It follows that the features of the living marine resources of the regions have also changed over time. King (2005) cited several examples of decadal-scale changes in biological production and community composition that occurred around 1977 and in the 1990s.

A chronology of inter-decadal climatic changes affecting the North Pacific Ocean, from measured atmospheric pressure and air temperature data from the late eighteenth century, was compiled by Minobe (1999). He speculated that the first "recorded" regime shift occurred in 1890. This was followed by

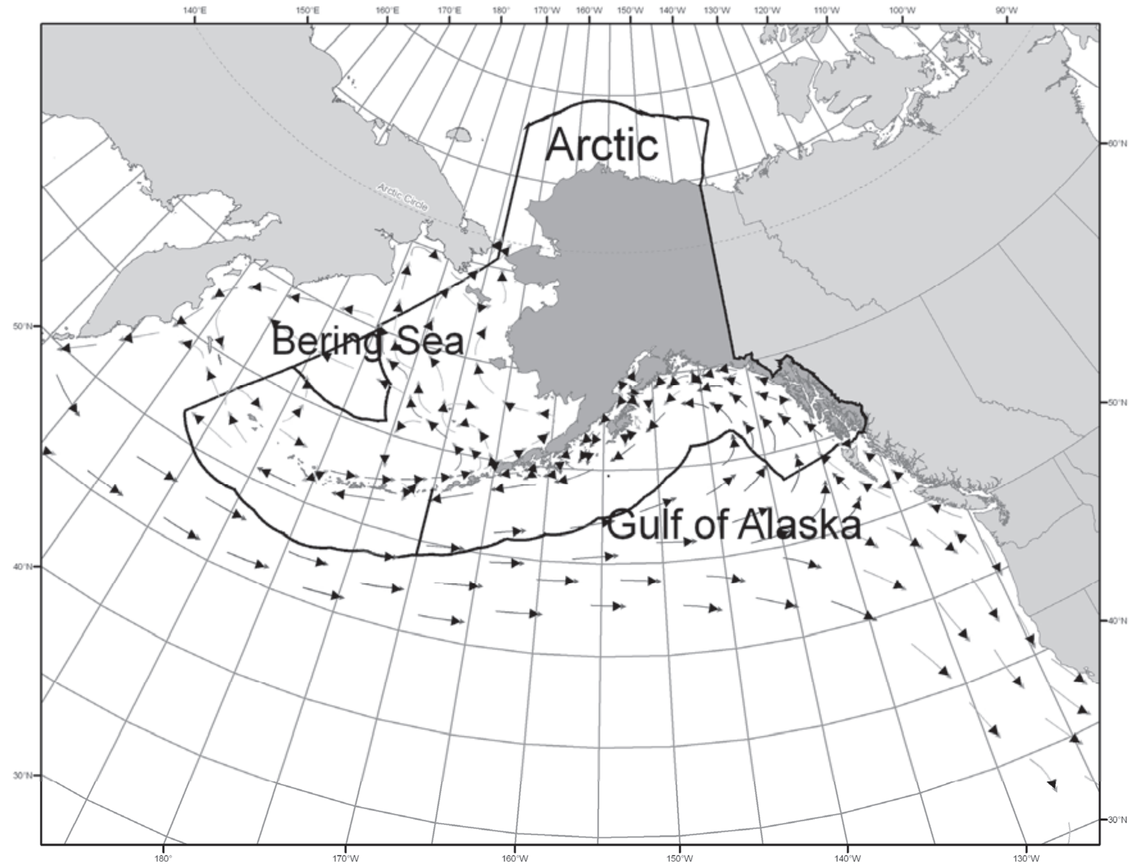

Fig. 88 Generalized surface current circulation of the Gulf of Alaska (GOA) and Bering Sea–Aleutian Islands (BSAI) regions.

several regime shifts, with each regime lasting 22 to 34 years. The scientific literature now generally recognizes that regime shifts occurred in 1925, 1947, 1977 and 1989. Regime shifts are not confined to the last 100 years. Paleo-ecological records show that regime shifts have occurred throughout the centuries but that the duration of detectable regimes have diminished from 50–100 years to 20–30 years and even to 10 years in most recent history.

More recently, the environmental regime of the North Pacific Ocean has been widely recognized to have shifted in 1976/77. The climate shift was associated with an abrupt transition from a negative to a positive phase of the PDO. Significant changes appear to have occurred for the ocean environment and the LMRs. Hare and Mantua (2000) assembled and examined 100 environmental time series (31 climatic and 69 biological) for evidence of biological and physical responses to these regime shift signals. They presented examples which illustrate that such signals were more evident in some areas than others. For example, the GOA environment does not appear to have shifted as much as the Bering Sea, and conditions appeared to have returned to near normal with less year-to-year variability.

Warming Influence on the Physical Environment

Temperature anomalies in the GOA and Bering Sea illustrate a relatively warm period in the late 1950s followed by cooling, especially in the early 1970s, and then followed by a rapid temperature increase in the latter part of that decade. Since 1983, the temperature difference between the GOA and Bering Sea has jumped from about 1.1°C to about 1.9°C (U.S. GLOBEC, 1996). Subsurface temperature anomalies for the coastal GOA (GAK1, 60°N, 149°W) also show a change from the early 1970s to the 1980s similar to that observed in the sea surface waters (U.S. GLOBEC, 1996).

Changes in ocean temperature on a shorter time basis can be quite variable, and often can mask long-term trends in ocean warming. Actual measurements of average summer water temperature in the Bering Sea recorded from 329 standard trawl stations sampled by the National Marine Fisheries Service (NMFS) crab–groundfish trawl surveys from 1982 to 2004 show this pattern (Fig. 89, upper panel). Over this 22-year period, the variation between the lowest and highest average surface temperatures was 4.88°C. However, there was a dramatic increase in surface temperature from a low of 3.69°C in 1999 to 8.24°C in 2004, a difference of 4.55°C in 5 years. The average bottom water temperature was steadier, and increased by 2.64°C over the same 5-year period. In the GOA, water temperatures recorded from the NMFS trawl surveys are both higher at the surface and near the sea bottom than the corresponding temperatures in the eastern Bering Sea (Fig. 89, lower panel). This is probably due to the winter ice cover in the Bering Sea. In areas of the GOA NMFS bottom trawl survey, where the bottom depths are less than 50 m, the bottom temperature has increased from 1984 to 2005 (Martin, 2005). At all other surveyed depths, the bottom temperature in the GOA has not shown a trend (Martin, 2005).

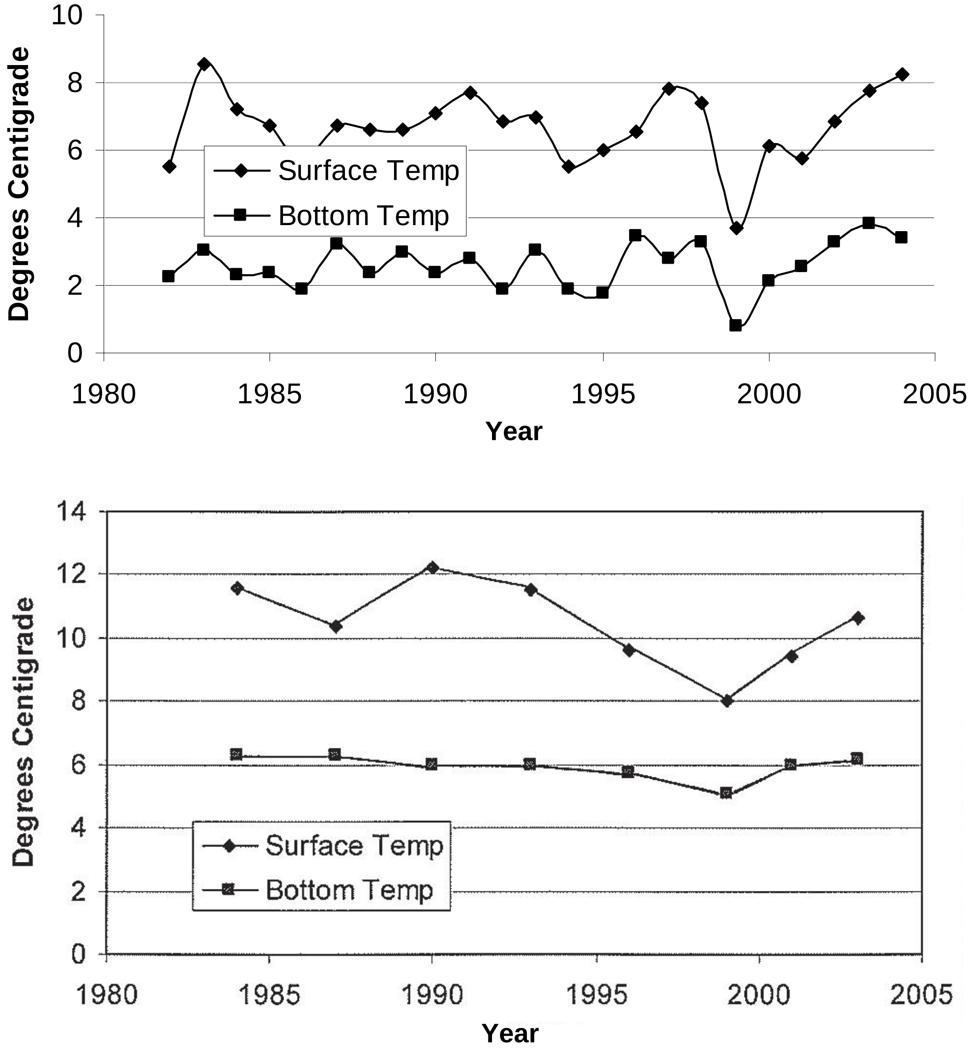

Fig. 89 Average water temperature recorded from National Marine Fisheries Service (NMFS) trawl surveys in the eastern Bering Sea (329 standard stations) from 1982 to 2004 (upper panel) and in the Gulf of Alaska (750–900 stations) from 1984 to 2004 (lower panel).

How will these higher temperature variations manifest themselves on the LMRs on a short-term basis and how would they mask the longer term effect of a gradual warming of the oceans on these same resources? These are important distinctions that may be difficult to determine. We tend to use large-scale climate indices to integrate and serve as proxies of environmental change in ecological conditions over time, but we know that short-term variability can mask and overwhelm some longer term trends. Thus, the response of ecological processes to longer term climatic warming can be difficult to determine. A fundamental conclusion from these indices is that no single index can adequately relate the complexities of climate variability in the diverse physical and ecological regions of the North Pacific. Thus, there is a need to review a wide range of variables.

Changes to the Climatic Environment

Gulf of Alaska

In general, climatologists have reasoned that a warming trend of the atmosphere over the North Pacific Ocean, especially at higher latitudes, would serve to decrease the meridional thermal gradient between northerly and southerly latitudes, and cause a more sluggish atmospheric circulation. This would result in an increase in absolute humidity, a decrease in storm intensity, and a northward shift in the storm track. The humidity increase would increase coastal precipitation. Some major ocean circulation effects that would follow an expected northward shift in the average line of zero wind stress curl, which separates the subarctic and subtropic gyres, are the weakening and northward shift of the core of the eastward flowing West Wind Drift and the northward shift of its bifurcation into the Alaska and California Currents.

With warming of the central North Pacific Ocean, the GOA is expected to have decreasing winter storm intensity and corresponding decreases in the input of positive vorticity (which drives the total flow) that could consequently diminish both the average northward transport in the Alaska Current and the westward transport in the Alaskan Stream. Other consequences in the central Gulf are expected to be less upwelling and less mixing, resulting in a shallower but warmer mixed layer tending to increase stratification.

Near the coastlines of the GOA, the expected added precipitation and glacial-ice-melt induced runoff would increase the nearshore sea surface water stratification even more. As temperatures warm, more of the increased winter precipitation would fall as rain, shifting the present fall maximum in river runoff earlier in the year closer to the time of maximum wind stress. Although the increased fresh water would add to the baroclinic structure, the decrease in wind stress along the coast would weaken the confinement of fresh water along the coast, thus weakening the baroclinic gradient and the Alaska Coastal Current.

The postulated reduction in strength of the Alaska Coastal Current would affect the transport of nutrients along the shelf, and diminished downwelling on the shelf would tend to reduce the cross-shelf flux of nutrient-poor waters at upper levels. This mechanism would be counteracted by less mixing by wind. Thus, there would be an unknown net effect on nutrient concentrations over the shelf. The timing of the spring bloom would probably occur earlier since the water would be warmer, and the formation of the spring mixed layer could be earlier.

Bering Sea–Aleutian Islands

The expected effects of a warming ocean environment should be greater in the Bering Sea where the presence of sea ice is a major contrast from the GOA. The warming in the Bering Sea is also expected to be greater due to the positive feedback from less snow cover and sea ice, hence a lower albedo. Changes in the atmosphere which drive the speculated changes in the ocean include increases in air temperature, storm intensity, storm frequency, southerly winds, humidity, and precipitation. Expected increases in precipitation plus snow and ice melt would lead to an increase in freshwater runoff. The only decrease would be in sea level pressure which is associated with the northward shift in the storm track. Although the location of the maximum in the mean wind stress curl will probably shift poleward, how the curl is likely to change is unknown. It is the net effect of the storms that largely determines the curl and there is likely to be compensation between changes in the frequency and intensity of the storms.

Ocean circulation decreases are likely to occur in the major current systems: the Alaskan Stream, Near

Strait Inflow, Bering Slope Current, and Kamchatka Current. Competing effects of ocean variables on currents make changes in the Unimak Pass inflow, the shelf coastal current, and the Bering Strait outflow unknown. Changes in hydrography should include increases in sea level, sea surface temperature, shelf bottom temperature and basin stratification. Decreases should occur in mixing energy and shelf break nutrient supply while competing effects make changes in shelf stratification and eddy activity unknown. Ice extent, thickness, and brine rejection are all expected to decrease. The thawing and loss of sea ice would have great effects on the timing and scale of biological events and processes in the Bering Sea. As sea ice coverage retreats northward and at earlier periods, ocean circulation would be affected which would trigger changes in biological productivity in unknown ways.

The Arctic

The Arctic is predicted to be the most affected of the three Alaska ecosystems, by warming trends according to a 4-year scientific assessment of climate change to the Arctic Ocean conducted by an international team of 300 researchers for the Arctic Council of eight nations (ACIA, 2004). Warming at the more northerly latitude is enhanced by positive feedback. Snow and ice reflect 80 to 90% of solar radiation back into space, but when these white surfaces disappear, more solar radiation is absorbed by the underlying land or sea as heat. This heat, in turn, melts more snow and ice.

The Arctic may lose 50 to 60% of its ice distribution by 2100 according to the average of five climate models run by the scientists from the Intergovernmental Panel on Climate Change (IPCC, 2001). This prediction has been based on the Arctic projections of the IPCC's "middle scenario", where gas emissions are double their pre-industrial level. Another reason for the Arctic's environmental sensitivity is that the air there is extremely dry compared to air at lower latitudes. This means that less energy is used up in evaporating water, leaving more as heat.

Since the northern ice cap is warming at twice the global rate, there would be serious consequences for the planet, although there may also be benefits. These consequences include substantial rises in sea level on a global scale. Locally, there would be drastic changes to physical, ecological and human systems. How these changes would interact are the research goals of the Arctic Climate Impact Assessment Project.

The loss of sea ice in the Arctic and Bering Sea LMEs is anticipated to have great consequences to the timing and scale of biological events which would trigger downstream implications to all the organisms in the ecosystems. Thus, there would be anticipated changes to the components and dynamics of the species. The ecosystems will be undergoing change and transition as ocean conditions change until some order of stability is reached for the physical dynamics of these two large LMEs.

Warming Influence on the Biological Environment: Key Species

The species groups addressed in this report include some of the more important commercially harvested species off Alaska: Pacific salmon, Pacific herring, some dominant groundfish species (like walleye pollock and Pacific halibut), and shellfish. They are described briefly below. For more comprehensive descriptions of these and other living marine resources in the region see NMFS (1998, 1999, 2004). The potential impacts on marine fish species in the Arctic region will not be addressed as little is known of these resources. The ACIA (2004) report on the "Impacts of a Warming Arctic" addresses impacts mainly to terrestrial animals and, in the case of marine species, only to marine mammal and seabird resources.

Pacific Salmon

Five species of Pacific salmon rear in the GOA and Bering Sea. All spend the majority of their ocean life in offshore pelagic waters, bounded by brief periods of migration through coastal areas as juveniles and returning adults.

Pink salmon (*Oncorhynchus gorbuscha*)

Fishery and biology

Pink salmon are the most abundant species of Pacific salmon in Alaska (Fig. 90), accounting for 40 to 70% of the total harvest each year. During the past 33-year period (1970–2003), pink salmon have comprised 58% of the average annual commercial harvest of salmon in Alaska. They are harvested mostly in southeastern, south-central, and Kodiak Island regions of the state (Eggers, 2004).

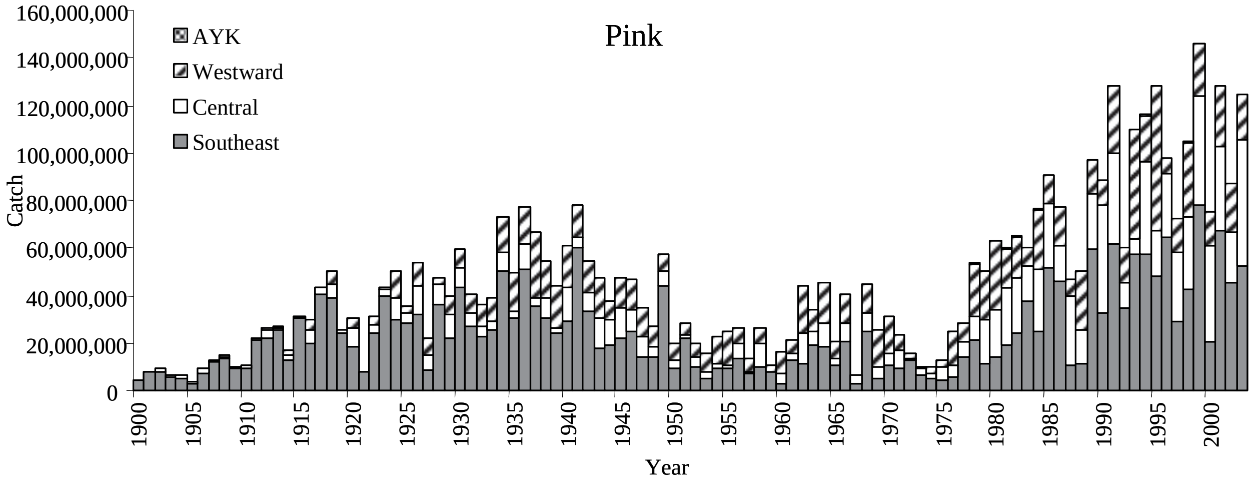

Fig. 90 Historical catch of pink salmon by area in Alaska from 1900 to 2003 (ADF&G, 2003; Eggers, 2004; NPFMC, 2004, Appendix D). AYK includes the areas of Norton Sound and the Arctic Ocean northward, the Yukon River mouth, the Kuskokwin River mouth, and the Bering Sea north of Cape Newenham. Westward includes areas north and west of Unimak Pass. Central includes areas from Cape Suckling to Unimak Pass. Southeast includes areas from the British Columbia border to Cape Suckling.

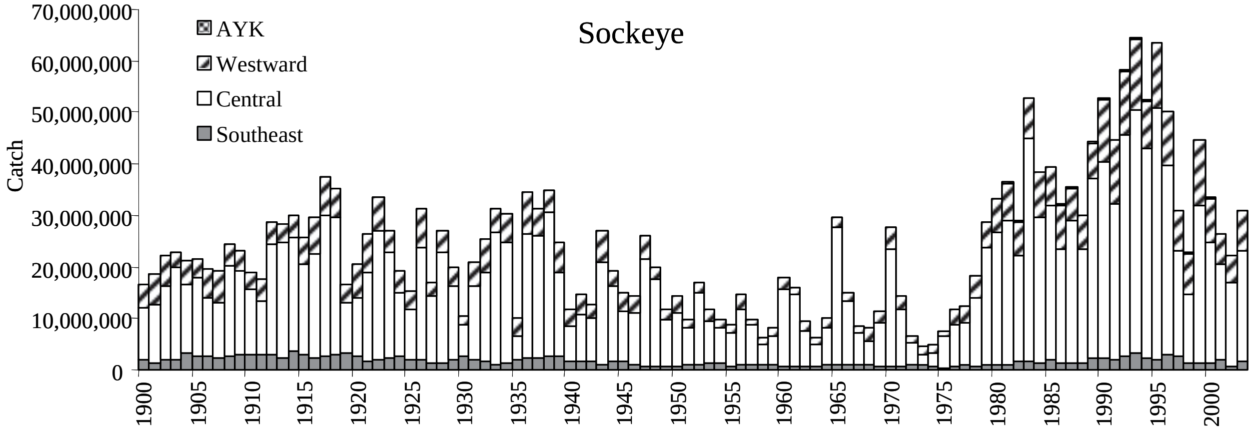

Fig. 91 Historical catch of sockeye salmon by area in Alaska from 1900 to 2003 (ADF&G, 2003; Eggers, 2004; NPFMC, 2004, Appendix D). Refer to Figure 90 for legend descriptions.

The life history cycle of pink salmon is unique as the species always matures and spawns at 2 years of age. This cycle is genetically fixed so that spawners in even-numbered years are always separate and distinct from spawners in odd-numbered years. Throughout much of its range the species has viable populations in both odd- and even-numbered years. However, in some areas, pink salmon only occur mainly in one or the other cycle year. In Bristol Bay and western Alaska, the dominant runs are in even-numbered years, whereas in the Pacific Northwest near their effective southern limit, the runs are dominantly in odd-numbered years.

Sockeye salmon (*Oncorhynchus nerka*)

Fishery and biology

Sockeye salmon are the second-most abundant salmon species caught in Alaska (Fig. 91), accounting for roughly 27% of the harvest in recent years (ADF&G, 2003). Sockeye salmon provide a greater dollar value to fishermen than all other commercially caught salmon species in Alaska combined, usually yielding from 60 to 70% of Alaska's ex-vessel value of the annual salmon harvest. In more recent years, however, world salmon prices have declined significantly, although there was a small price rebound in 2004 which seems to be holding. The largest fisheries for sockeye salmon occur in Bristol Bay, Cook Inlet, Alaska Peninsula–Aleutian Islands, and Kodiak Island regions while other significant fisheries for this salmon also occur in southeastern Alaska, Prince William Sound, and Chignik regions.

The most common sockeye salmon life history pattern shows that juveniles rear in lakes for 1 to 2 years before migrating seaward as smolts. The large lake complexes on Bristol Bay rivers provide this necessary life history component and form a critical part of the important fishery in this region. The Bristol Bay fishery is concentrated in a narrow window of time from late June until mid-July when millions of returning adult sockeye salmon pour into Bristol Bay rivers from the ocean.

During a 5-year period (1992–1996), returns to Bristol Bay ranged from 29.6 to 44.4 million fish and averaged 36.5 million sockeye salmon per year. The return to Bristol Bay in 1997, however, was only 18.9 million, with a fishery harvest of 12.1 million. This unexpectedly low return of sockeye salmon created a serious shortfall in the catch and incomes of fishermen and communities.

As bad as the 1997 sockeye salmon harvest in Bristol Bay was, commercial landings in 1998 were even worse, with a harvest of only 10 million fish. Returns improved somewhat in 1999 and 2000, with commercial catches of 26.1 and 20.5 million sockeye salmon, respectively. More recently, the returns have declined again, with commercial catches of only 14.2, 10.7, and 14.9 million fish, respectively, in 2001, 2002, and 2003 (ADF&G, 2003). All of these recent harvest levels of sockeye salmon in Bristol Bay are well below previous decadal averages.

Several hypotheses have been suggested by Dr. Bill Heard (NMFS, Auke Bay Lab., pers. comm.) to explain recent shortfalls of sockeye salmon returning to Bristol Bay. One hypothesis is that unusually warm, calm weather during summers has resulted in high water temperatures causing high mortality and changes in migration behavior of adult salmon entering the bay. Other possible causes include changes in freshwater or ocean rearing conditions that affect growth and survival of juveniles or immature adults, increased predation at sea, interception by other fisheries, disease, and in some instances over-escapements on spawning grounds. The true causes of these shortfalls, which likely involve a combination of many factors, remain unknown.

Chum salmon (*Oncorhynchus keta*)

Fishery and biology

Over a 33-year period (1970–2003), chum salmon have accounted for 10% of Alaska's salmon harvest (Fig. 92). Over the past 8-year period (1996–2003), the average annual chum salmon harvest across Alaska was 18.6 million fish, with the 2000 harvest well above this average, at a record 24.3 million fish (ADF&G, 2003). Currently, 60 to 70% of the commercially harvested chum salmon in Alaska occur in southeastern Alaska where hatcheries produce a significant portion of the catch.

Chum salmon runs in southwestern and western Alaska similar to sockeye salmon in Bristol Bay, have been well below long-term averages since 1995. Management of chum salmon fisheries in western Alaska is complicated by another commercial fishery at False Pass in the Aleutian Islands. Western Alaska chum salmon may spend part of their ocean life in the GOA. As maturing adults on their return migration, they funnel through the Aleutian passes into the Bering Sea. The False Pass fishery targets primarily sockeye salmon returning to Bristol Bay and must be managed to not over-harvest chum salmon destined for the Kuskokwim and Yukon Rivers in western Alaska. The Alaska Board of Fisheries has placed major restrictions on the False Pass fishery in an effort to help rebuild depleted chum salmon resources in western Alaska. Chum salmon in western Alaska not only are an important part of commercial fisheries in that region but are also a significant subsistence resource for local residents.

Coho salmon (*Oncorhynchus kisutch*)

Fishery

Commercial catches of coho salmon across Alaska totaled 4.1 million fish in 2003, 0.5 million less than the recent 6-year average harvest levels of 4.6 million fish (ADF&G, 2003), but still well above the record low catches in the 1970s (Fig. 93). This relatively high commercial harvest was due to generally favorable returns in southeastern Alaska where 3 million or more coho salmon from hatchery and wild stock production were caught in 4 out of the last 6 years. Coho salmon, along with sockeye and chinook salmon, are popular target species in recreational fisheries throughout Alaska.

Chinook salmon (*Oncorhynchus tshawytscha*)

Fishery and biology

The annual commercial harvest of chinook salmon in Alaska has ranged between 300,000 and 700,000 fish over the past two decades (Fig. 94). The statewide 13-year (1991–2003) average annual harvest was 559,000 fish (ADF&G, 2003). In general, chinook salmon are the first species each year to begin spawning migrations into Alaska rivers. Only in a few Bristol Bay and western Alaska rivers are fisheries permitted to directly target these early returning runs. However, in fisheries targeted on other salmon, chinook salmon are often taken incidentally.

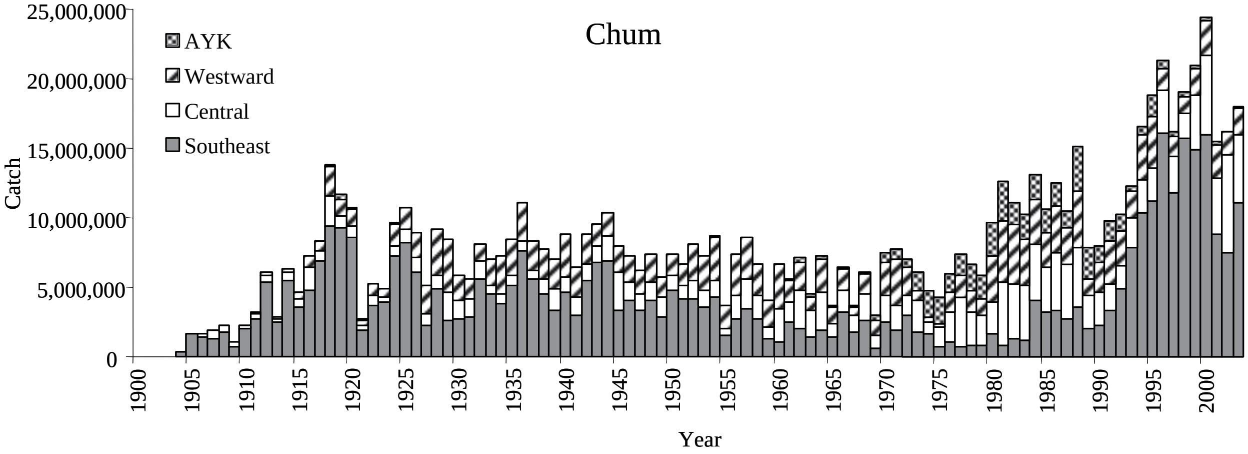

Fig. 92 Historical catch of chum salmon by area in Alaska from 1900 to 2003 (ADF&G, 2003; Eggers, 2004; NPFMC, 2004, Appendix D). AYK includes the areas of Norton Sound and the Arctic Ocean northward, the Yukon River mouth, the Kuskokwin River mouth, and the Bering Sea north of Cape Newenham. Westward includes areas north and west of Unimak Pass. Central includes areas from Cape Suckling to Unimak Pass. Southeast includes areas from the British Columbia border to Cape Suckling.

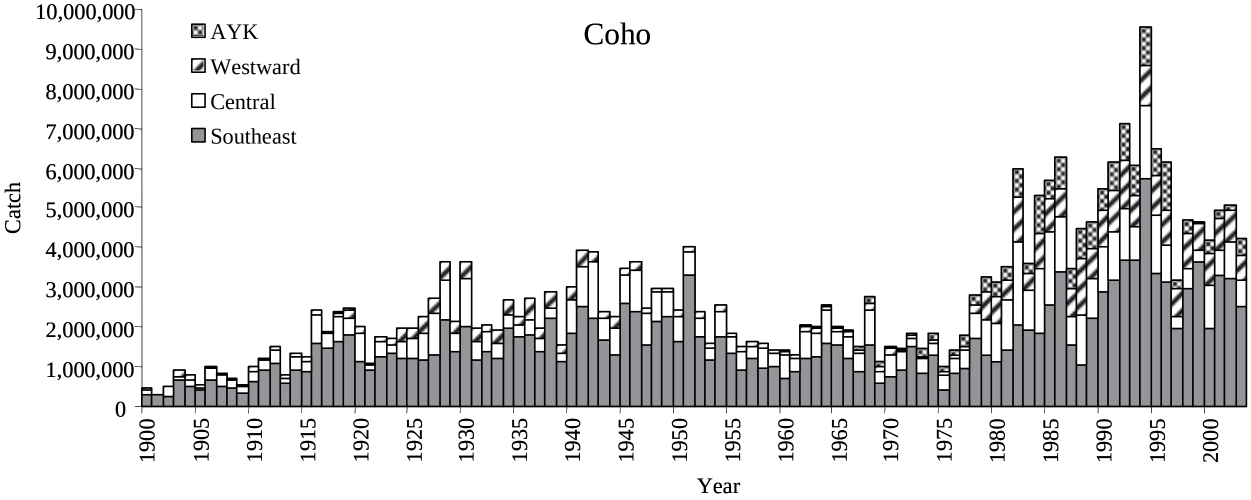

Fig. 93 Historical catch of coho salmon by area in Alaska from 1900 to 2003 (ADF&G, 2003; Eggers, 2004; NPFMC, 2004, Appendix D). Refer to Figure 92 for legend descriptions.

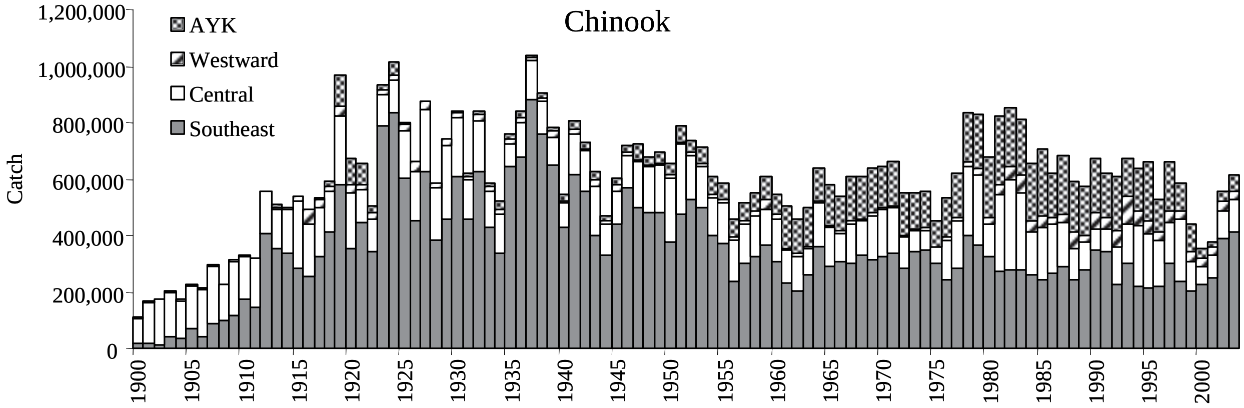

Fig. 94 Historical catch of chinook salmon by area in Alaska from 1900 to 2003 (ADF&G, 2003; Eggers, 2004; NPFMC, 2004, Appendix D). Refer to Figure 92 for legend descriptions.

The region-wide chinook salmon harvest in southeast Alaska, where significant numbers of non-Alaska origin fish are caught, is normally regulated by a quota under provisions of the Pacific Salmon Treaty.

Effects of Climate Change on Pacific Salmon in the Fishery

Pacific salmon range over the entire North Pacific from 40°N to well over 65°N, or higher, in ice-free areas. The different species have survived over thousands of years and seem to have great adaptability to climatic changes in order to survive and perpetuate. The life history of salmon has both marine and freshwater phases. Their survival is strongly determined by events in their freshwater life phases where they spawn and where eggs and smolts are nurtured in streams and lakes before they go to sea. Many human activities impinge upon this phase of their life cycle and the phase when adults struggle to reach their natal spawning grounds. The effects of urbanization and other human activities on land, in fresh waters, and nearshore waters would seem to have a greater impact on the future of salmon than would ocean warming and other climatic changes in the marine phases of their life.

Figure 95 (provided by Dr. Nathan Mantua, Univ. of Washington, pers. comm.) shows the typical Pacific salmon life cycle in the Pacific Northwest and how atmospheric warming and other environmental changes could affect various phases of their life cycle. Similar impacts are also expected for salmon stocks off Alaska. The diagram states that oceanic and atmospheric warming will increase snow melt and increase fall/winter floods and water flows which would affect salmon eggs laid in gravel beds. In the following summer, when the smolts are in streams, higher summer temperatures could diminish the oxygen content of the water and increase salmon mortality. Warmer temperatures could also affect smolt migration and increase timing mismatches with their zooplankton prey base, essential as the smolts enter salt water. It is hypothesized that salmon survival is determined early in its marine life when mortality is high.

In the oceans, changes to the salmon food web and supply could negatively or positively affect survival and growth of salmon. Figure 95 only illustrates where changes would likely take place; actual impacts at these various life phases are difficult to quantify. It appears, however, that negative impacts of atmospheric warming should be more strongly felt in the freshwater environment than in the marine environment. Still, it may be surmised that Pacific salmon may have great adaptability to climatic changes, as the species has lasted over so many centuries over such wide latitudinal and geographical ranges that encompass great variations in their environment and food webs.

On a historical perspective, Alaskan salmon production from the mid-1970s to the late 1990s has been increasing and is at near all-time highs. This may be attributed to changes in ocean and atmospheric conditions that increased survival, as well as enhanced hatchery releases (Beamish and Bouillon, 1993; Ishida *et al.*, 1995; Mantua *et al.*, 1997; Coronado and Hilborn, 1998). These increasing catch trends of the various salmon species are shown in Figures 90 to 94. The increased production in some

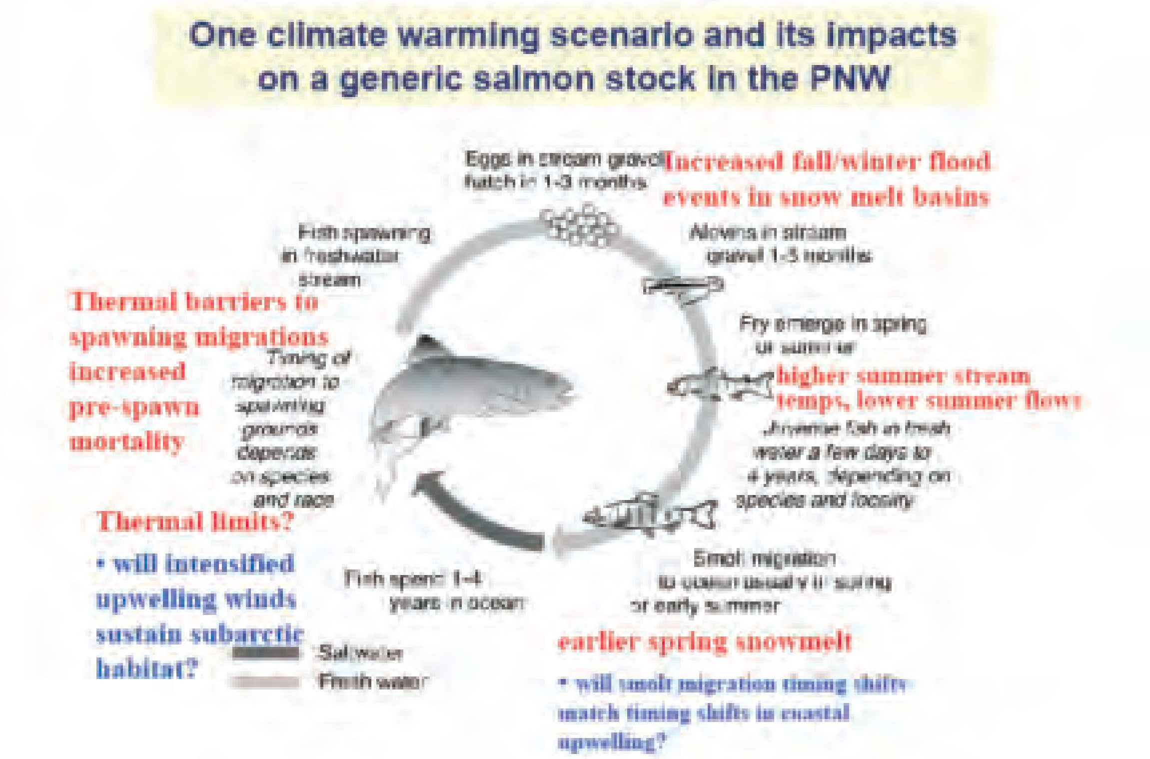

Fig. 95 One climate warming scenario and its impact on a generic salmon stock in the Pacific Northwest (figure provided by Nathan Mantua, University of Washington).

cases, however, was accompanied by a decrease in average salmon weight at maturity from 1975 to 1993 for some sockeye, pink, and chum salmon stocks in southeast, central, and western Alaska (Bigler *et al.*, 1996). Many scientists believe that these decreases in average weight were due to density-dependent growth caused by increased competition for food in the ecosystem (Ishida *et al.*, 1993; Pyper and Peterman, 1999). The decreasing average size trend for the salmon species, however, was not apparent for the northern (Arctic–Yukon–Kuskokwim) stocks. In addition, the general decreasing trend in average salmon weight for the species off Alaska appears to have leveled off within the last 5 years.

Pacific herring (*Clupea pallasii*)

Fisheries and climatic influences

Research and management of Pacific herring fisheries off Alaska are the responsibilities of the Alaska Department of Fish and Game. There are three main areas where Pacific herring (*Clupea pallasii*) are harvested commercially: Prince William Sound (PWS), southeast Alaska, and the Togiak district.

Prince William Sound herring

Strong recruitment events occurred in this area approximately every 4 years in the 1980s (Fig. 96). The recruitment of age-3 fish from the 1984 and 1988 year classes were particularly large (~ 1 billion fish in 1987). The pre-fishery run biomass estimate peaked in 1988 and 1989 at more than 100,000 t (biomass is not shown but is inferred from Fig. 96). The 1993 biomass dropped to less than 30,000 t (Marty *et al.*, 2003). This stock collapsed and the biomass from 1993 to 2004 has remained at levels less than half of the 1980 to 1992 average of 84,000 t.

The PWS Pacific herring fishery is managed to allow harvest of less than 20% of the biomass above a spawning biomass threshold of 20,020 t. Since the stock collapsed in 1993, purse seine sac roe harvest has occurred only in 1997 and 1998 (2 out of 13 years). The fishery was also closed in the fall of 2004 and spring of 2005 because the projected biomass was under the threshold spawning biomass.

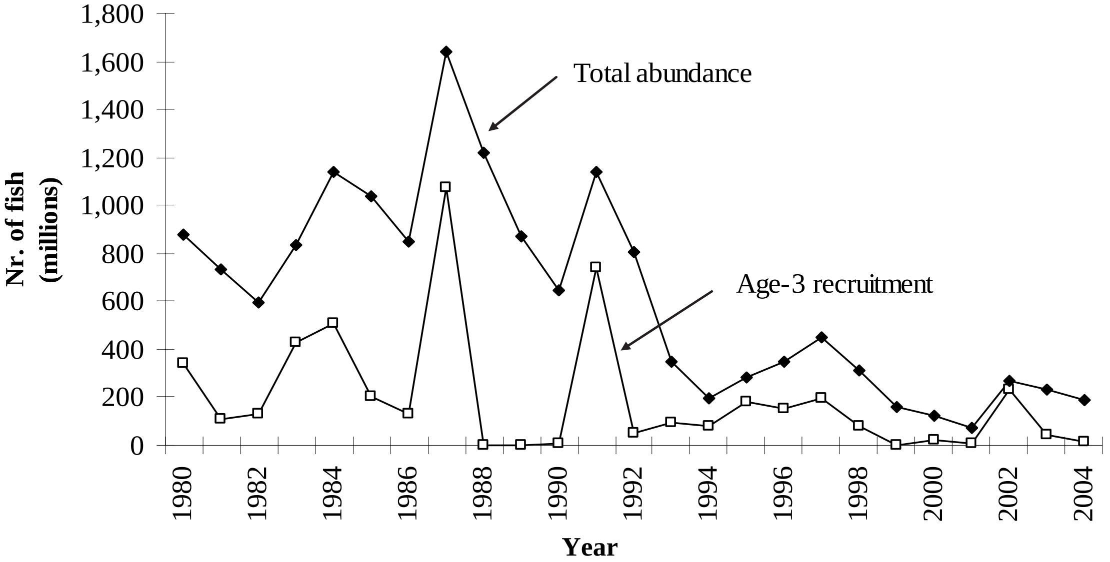

Fig. 96 Age-3 recruitment and total pre-fishery abundance of Pacific herring in Prince William Sound, 1980–2004 (from ADF&G, 2003; NPFMC, 2004, Appendix D).

The variability of Pacific herring recruitment in PWS was related to at least three main factors: large-scale environmental factors (Williams and Quinn, 2000), smaller-scale environmental factors (Norcross *et al.*, 2001), and disease (Marty *et al.*, 2003, 2004). Disease assessments conducted from 1993 through 2002 indicated that viral hemorrhagic septicemia virus (VHSV) and associated ulcers were related to population declines in 1993 to 1994 and 1998. The parasite *Ichthyophonus hoferi* was related to a population decline in 2001 (Marty *et al.*, 2004).

Southeast Alaska herring

Spawning biomass of Pacific herring in southeast Alaska often fluctuated markedly from year to year and rarely exhibited consistent, monotonic trends (Fig. 97). Since 1980, seven of the nine primary locations have exhibited long-term trends of slightly increasing biomass. One area (Craig) has not shown any notable long-term trend, and biomass in one area (Kah Shakes-Cat Island) has had a pronounced downward trend. There have been major fluctuations around these long-term trends, with periods of both increasing and decreasing trends over the shorter term.

There does not appear to be clear decadal-scale variability of Pacific herring recruit abundance in the three widely recognized climate regimes of 1978–1988, 1989–1998 and post-1998 in the North Pacific. The number of age-3 recruits has been estimated for Kah Shakes-Cat Island, Craig, Seymour Canal, Sitka, and Tenakee Inlet for most years since 1980. The number of age-3 recruits has been estimated for west Behm Canal, Ernest Sound, Hobart Bay–Port Houghton and Hoonah Sound for most years since 1995. Overall recruit abundances were highest in 1980, 1987, 1991, and 1996. However, this pattern was not consistent across all spawning locations. Only one stock, Kah Shakes-Cat Island, showed a distinct decreasing trend in recruit abundance over time. The recruit abundance of Sitka herring, the stock with the greatest annual recruit abundance, was above the 24-year median in 8 out of the last 9 years.

Togiak herring

Temporal trends in Togiak herring abundance show that total abundance in much of the 1980s was above the 1978–2003 average, but fell below in 1989 and has remained below average since, with the exception of slightly above-average values in 1991 and 1992 (Fig. 98). The high abundance estimates in the early 1980s made from model projections may not have been real, as Alaska Department of Fish and Game aerial survey data for the same time period conflicted with those estimates, showing much lower biomass. This discrepancy has not yet been resolved, but the aerial survey data are currently being used to "ground truth" for model estimates. The present status of the Togiak herring stock has been changed from "nominal decline" to "stable" as the stronger 1996 and 1997 recruitment enters the fishery in greater numbers.

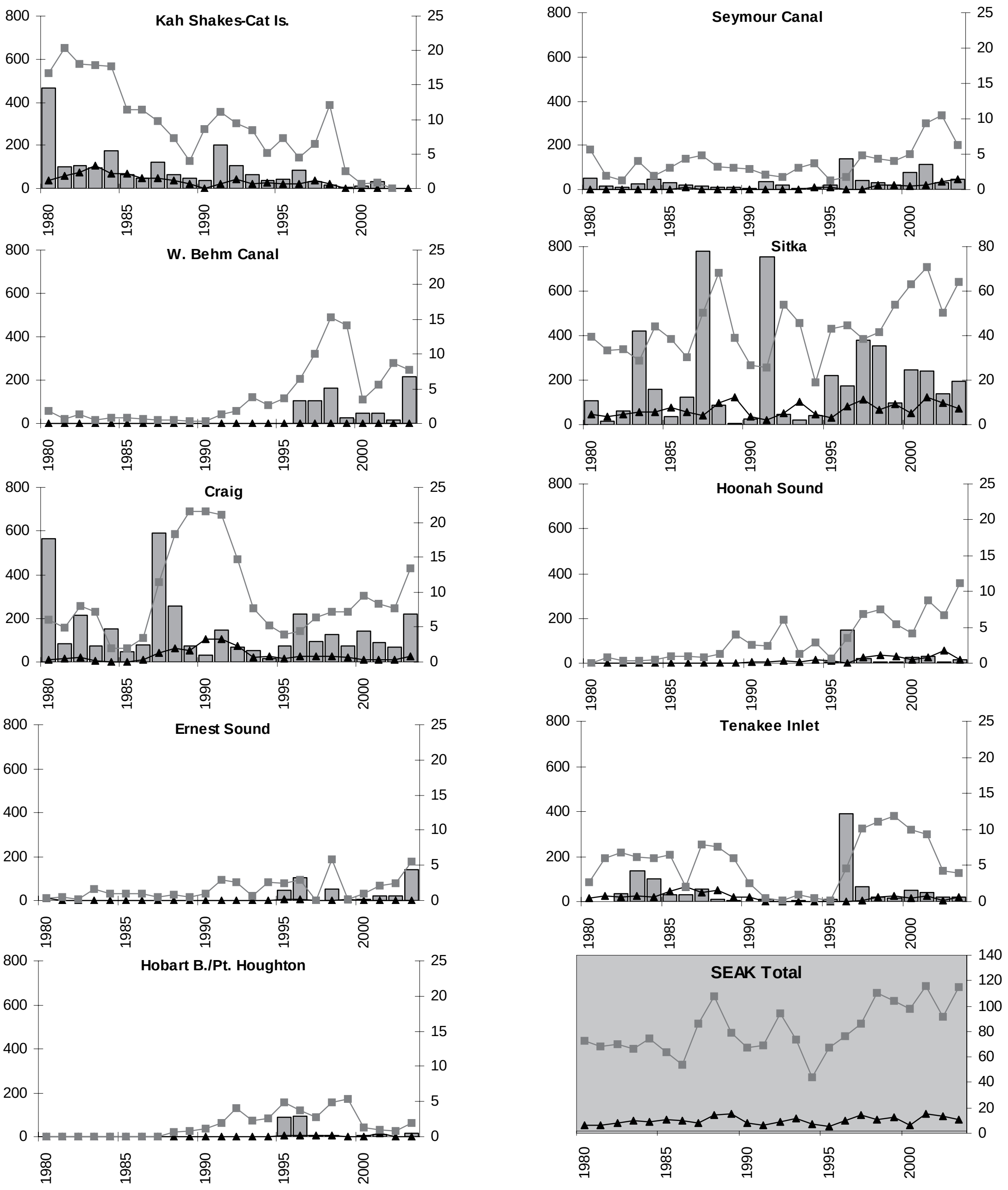

Fig. 97 Estimated herring spawning biomass (tons, gray squares); catch (tons, black triangles), and age-3 recruits (millions of fish, gray bars) in nine areas of southeast Alaska from 1980 to 2003. Total biomass and catch for southeast Alaska (SEAK) are shown (bottom right panel). Recruits were not estimated in all years in all areas. Therefore, missing values may not be zero estimates (from ADF&G, 2003; NPFMC, 2004, Appendix D).

Pacific herring recruitment trends are highly variable, with large year classes occurring at regular intervals of approximately every 9 to 10 years (Fig. 98). These large recruitment events drive the Togiak herring population. Environmental conditions may be the critical factor that influences their recruitment strengths. Williams and Quinn (2000) demonstrated that Pacific herring populations in the North Pacific were closely linked to environmental conditions, with temperature having the strongest influence. It has generally been recognized in fisheries science that the larval stage of herring life history is the most important factor for determining year-class strength (Cushing, 1975; Iles

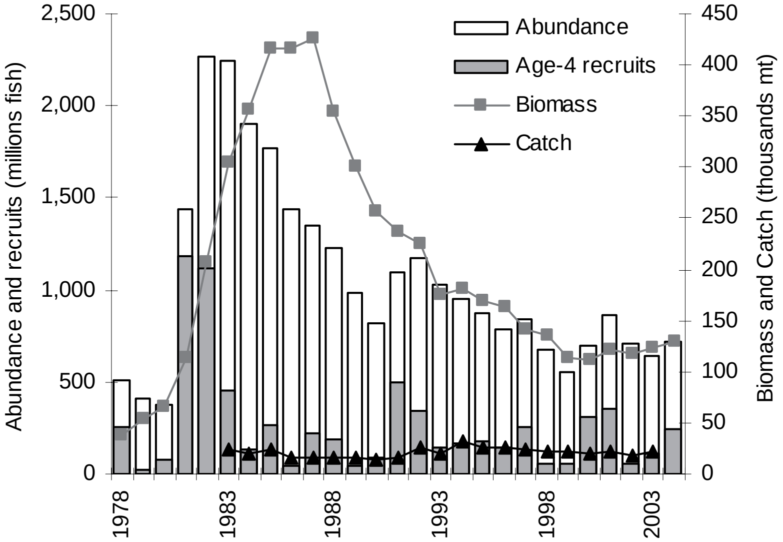

Fig. 98 Total abundance, age-4 recruits, mature biomass and total harvest of Pacific herring in the Togiak district of Bristol Bay from 1978 to 2004 (from ADF&G, 2003; NPFMC, 2004, Appendix D).

and Sinclair, 1982). Thus, ocean conditions off Alaska at spawning run time are expected to greatly influence the strength of the year class. A closer examination of trends in sea surface temperature, air temperature, and Bering Sea ice cover will have to be further evaluated to determine their effects on herring recruitment.

Groundfish

Fisheries and biology

The groundfish complex is the most abundant of all fisheries resources off Alaska. The combined exploitable biomass of all the groundfish species is more than 23 million metric tons (t) off Alaska; 76% is in the BSAI region and the remainder is located in the GOA. The recent (2002–2004) harvest was 2.1 million t, or 9% of the total biomass. The rates of fisheries exploitation varied by species, but all were less than the overfishing rates determined under the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA). The main species of groundfish resources are walleye pollock (*Theragra chalcogramma*), Pacific cod (*Gadus macrocephalus*), yellowfin sole (*Limanda aspera*), northern rock sole (*Lepidopsetta polyxystra*), Atka mackerel (*Pleurogrammus monopterygius*), Pacific ocean perch (POP, *Sebastes alutus*), arrowtooth flounder (*Atheresthes stomias*), and sablefish (*Anoplopoma fimbria*).

The average eastern BSAI groundfish catch in recent years (2002–2004) was about 1.9 million t (Fig. 99), taken from the groundfish complex exploitable biomass of about 18 million t (Fig. 100). The dominant species harvested are walleye pollock (73%), Pacific cod (11%), yellowfin sole (4%), rock sole (3%), and Atka mackerel (3%). The rest of the species make up 1% or less of the total catch.

In the GOA, recent average catches were 170,000 t from 5.2 million t of exploitable biomass (Figs. 99 and 100). The dominant species harvested are walleye pollock (36%), Pacific cod (25%), flatfishes (14%), Pacific ocean perch and various species of rockfishes (13%), and sablefish (8%). The bulk of the total groundfish biomass (50%), however, is dominated by arrowtooth flounder.

Groundfish abundance for both the Bering Sea and the GOA regions are near historically high levels, although some are declining, albeit slowly in recent years. Biomass has remained relatively stable and catches have never reached their full acceptable biological catch (ABC) potential estimated for the resources (NPFMC, 2004). In the BSAI region, the ABCs for groundfish total more than 3 million t for

2005 and catches are limited to an optimum yield of 2 million t under the BSAI Groundfish Fishery Management Plan. While pollock and Pacific cod have been harvested closer to their ABCs, all the other groundfish species are generally underutilized. In the GOA region, ABCs for 2005 total almost 400,000 t while catches have been 167,000 t. Thus, most of the species, particularly flatfish species like arrowtooth flounder, have been underutilized. Many of the species are not harvested because they cannot be fully taken without violating other fishery regulations of bycatch restrictions on Pacific halibut, salmon, and crab species.

Walleye pollock (*Theragra chalcogramma*)

Fishery and biology

Walleye pollock (hereafter referred to as pollock) are highlighted in this report because of their dominance in the catch, and because their life cycle is strongly impacted by climatic events. Pollock produce the largest catch of any single species inhabiting the U.S. Exclusive Economic Zone (EEZ). The catch history of pollock in the BSAI and GOA is shown in Figs. 101 and 102, respectively. The three main stocks in the BSAI region, in decreasing order of abundance,

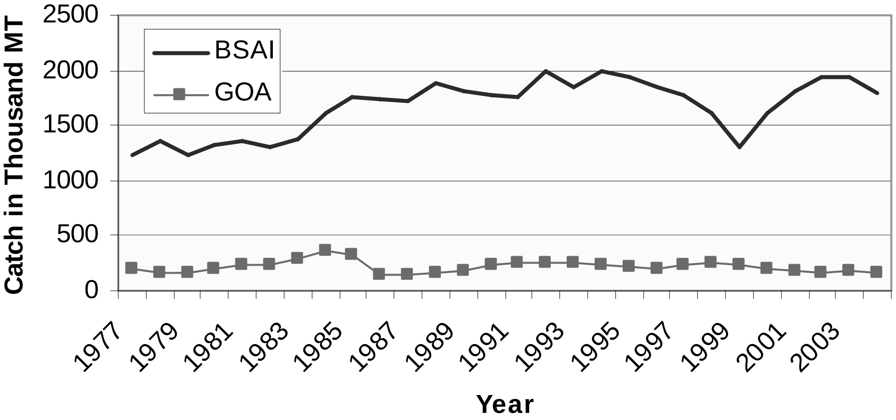

Fig. 99 Alaska groundfish catch (thousand metric t) in the Bering Sea–Aleutian Islands (BSAI) and Gulf of Alaska (GOA) regions from 1977 to 2004.

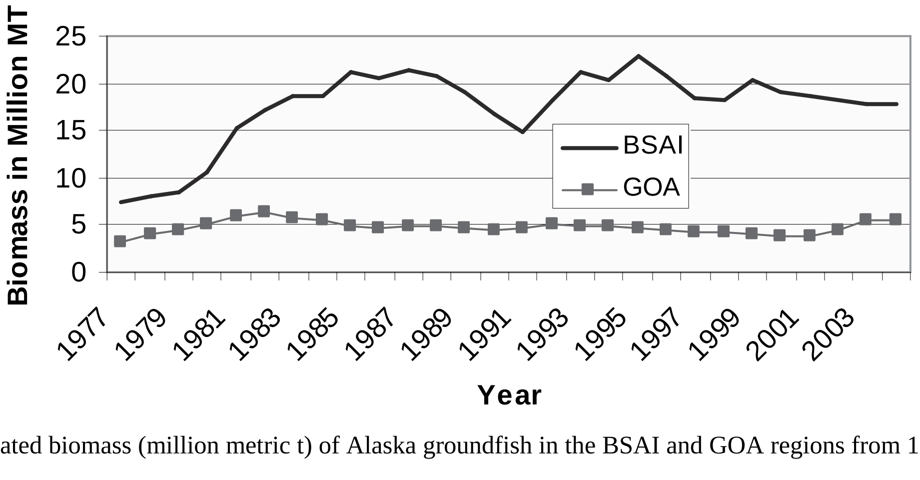

Fig. 100 Estimated biomass (million metric t) of Alaska groundfish in the BSAI and GOA regions from 1977 to 2004.

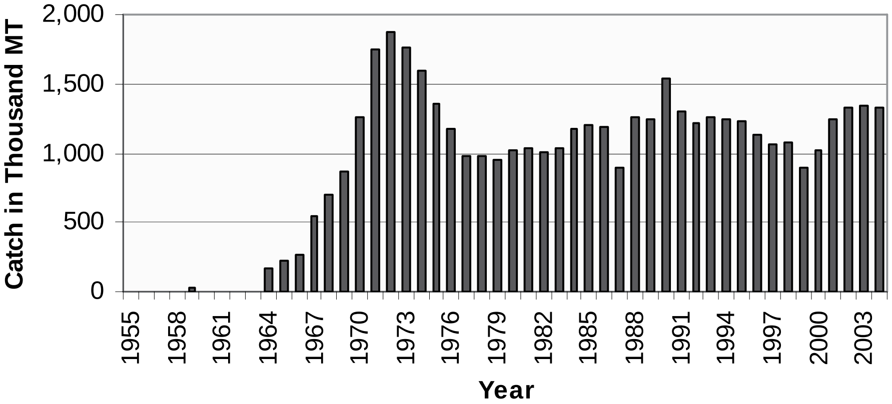

Fig. 101 Pollock catch (thousand metric t) in the Bering Sea–Aleutian Islands (BSAI) region from 1955 to 2004.

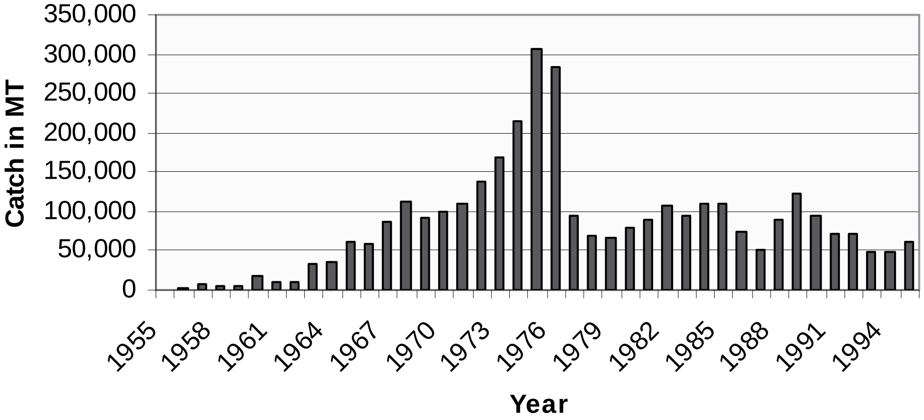

Fig. 102 Pollock catch (metric t) in the Gulf of Alaska (GOA) region from 1955 to 2004.

are eastern Bering Sea stock, Aleutian Basin stock, and the Aleutian Islands stock. The eastern Bering Sea pollock stock biomass has gone through three prominent production cycles as a result of variable strengths of recruiting year classes that are believed to be tied to climatic events. There are at least two stocks of pollock in the GOA, one originating from Shelikof Strait and the other east of Kodiak Island.

Walleye pollock stocks off Alaska are managed by NOAA Fisheries, in consultation with the North Pacific Fishery Management Council (NPFMC), within safe biological exploitation levels, while accounting for their ecological roles in the marine ecosystem. The catch levels and areas of fishing have been carefully controlled to reduce the risk of overfishing and to mitigate food competition with Steller sea lions (*Eumetopias jubatus*, listed as an endangered population in western Alaska and as a threatened population in eastern Alaska), and marine birds that prey on pollock. For the Bogoslof Island and the Aleutian Islands areas, where both pollock stocks are substantially below their long-term potential yields, target fisheries for pollock have not been allowed in recent years, and incidental catch limits have been imposed. The exception is a 19,000 t special allocation of pollock by Congressional law to the Adak Community in the Aleutian Islands area in 2005.

Climatic Influences

Pollock are widely distributed throughout the North Pacific Ocean in temperate and subarctic waters (Wolotira *et al.*, 1993), thus indicating a tolerance for a wide temperature range. They are a semi-demersal schooling fish, which becomes increasingly demersal with age. The species spawns in large aggregations at depths of 100 to 300 m in many spawning locations in the BSAI region. Spawning schools aggregate to spawn adjacent to the Aleutian Islands and over

Bogoslof Island in late February to early March, and in the southeastern Bering Sea in January. Spawning activities of other aggregated schools in more northerly locations are progressively later, with some taking place as late as May towards the U.S.–Russia maritime boundary. Thus, pollock are protracted open-ocean spawners that spawn over a wide geographical space and over a few months. In the GOA, the dominant aggregation of spawning pollock is in Shelikof Strait, although other spawning aggregations are found east of Kodiak Island. Harvestable adult concentrations can be found throughout the GOA, including Prince William Sound.

As the eggs and larvae rise and develop, they are subject to the vagaries of ocean currents. Thus, pollock are especially vulnerable during the early phase of their life cycle, when climatic events can strongly determine the success or failure of year classes. The species is relatively short-lived (natural mortality estimated at 0.3 years) and is a fast-growing fish. Females usually become sexually mature at 4 years of age and the maximum age is about 22 years.

The effects of ocean currents on the survival of the early life stages of pollock have been studied extensively in the GOA and the eastern Bering Sea by NOAA's Fisheries Oceanography Coordinated Investigations (FOCI) program. FOCI investigates the early life stages (eggs, larvae and early juveniles) of the species. Early each spring in the GOA, pollock spawn in Shelikof Strait and produce large batches of eggs that develop into larvae. In most years, the concentrations of larvae drift to the southwest with the Alaska Coastal Current during April and May (Fig. 103). In the Bering Sea, the number and size of spawning concentrations are larger than in the GOA. Spawning events start in early March near Bogoslof Island and along the Aleutian Islands and progress eastward and northward, lasting until as late as early May. Pollock eggs and larvae are carried by currents into the Bering Sea, generally east and northwards towards the eastern Bering Sea (EBS) shelf. Based on model predictions of pollock egg and larvae transport (Fig. 104) using the Ocean Surface Current Simulation (OSCURS) model, it has been speculated that larval survival would be more favorable if the larvae are carried onshore towards the EBS shelf, where food is expected to be more plentiful, than when they are carried offshore. The FOCI program has determined that large numbers of larvae are often found in eddies, where feeding conditions are favorable. The program found that first-feeding larvae have a higher survival rate during calm sea conditions than in storms and that in some years recruitment is largely determined by the end of the larval period.

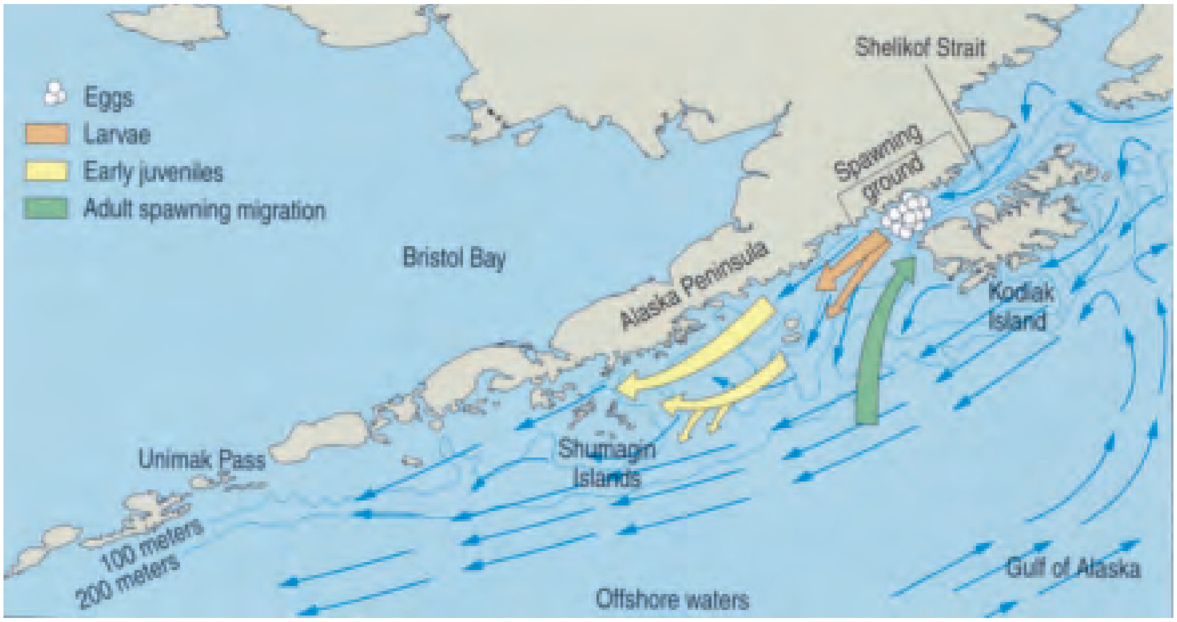

Fig. 103 Pollock spawning in Shelikof Strait and drift of their eggs and larvae with the currents, as determined by the Fisheries-Oceanography Coordinated Investigations (FOCI) program.

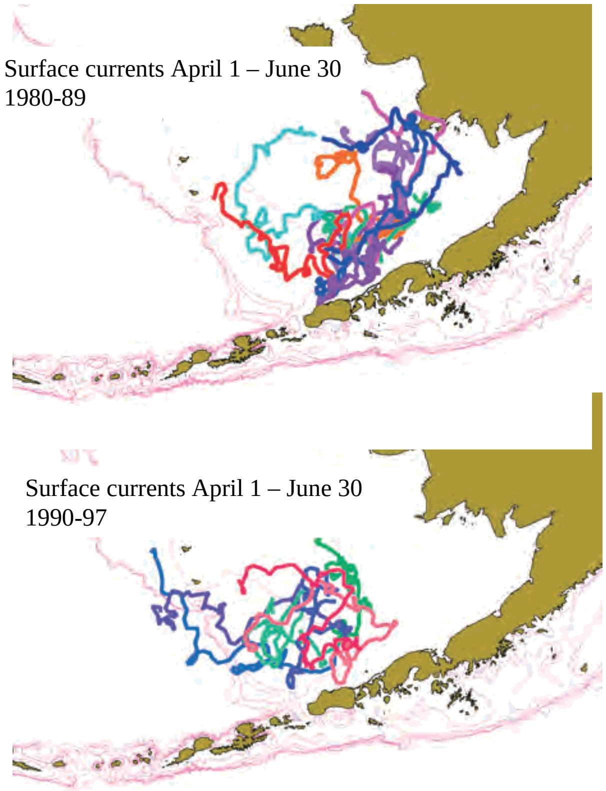

Fig. 104 OSCURS (Ocean Surface Current Simulation) model trajectories from starting point 56°N, 164°W from April 1 to June 30 for the 1980s (upper panel) and 1990 to 1997 (lower panel) (adapted from Wilderbuer *et al.*, 2002).

It is difficult to speculate how the warming of the GOA and Bering Sea would affect the finer aspects of current flow and how the resultant ocean environment would affect the plankton life that pollock larvae feed on when they hatch. The ocean environment would affect a whole sequence of prey–predator timing events that complicates how cascading events on the LMRs would take shape.

There is also the issue of water temperature preference for all the LMRs and whether there would be a northward shift in the center of distribution for pollock. Since the heat content of the ocean is held for a long time and if warming continues, it is likely that the centers of distribution for pollock and other groundfish species would shift also. It is too early to tell, whereas the shorter term climatic events in the GOA and regime shifts have masked any apparent shift in distributions.

One apparent shift in the location of pollock spawning concentrations appears to be in the vicinity of Bogoslof Island. Surveys conducted by the NOAA R/V *Miller Freeman* from 1988 to 2005 suggest that high concentrations of the fish that aggregated to spawn near Bogoslof Island in the late 1980s to early 1990s have shifted toward the Aleutian Islands, and that the concentrations have been getting smaller. It was unknown if this centroid shift is related to changes in the ocean environment or to depletion of the stock from intensive fisheries in the central Bering Sea Donut Hole area in earlier years. Intensive fisheries took place from 1986 to 1990 when more than a million metric tons of pollock were reportedly taken annually from the Donut Hole area. These fisheries seemed to have depleted the Bogoslof Island spawning stock. Could depletion of the stock in the Donut Hole area have caused the shifts in the centroids of spawning concentrations towards the Aleutian Islands? Could this shift be environmentally related? These are just two questions about variability and the mystery of species interactions with the environment.

Groundfish recruits per spawning biomass

As the ocean environment is expected to affect recruitment, one way to examine the relationship is to evaluate recruit per spawner biomass ratios. Median recruit per spawning biomass anomalies were calculated for each species to provide an index of survival for the BSAI and GOA regions (Figs. 105 and 106). In stocks that are abundant, the relationship between recruits and spawners may not be linear and density-dependent factors may limit recruitment. Under these circumstances, the pattern of recruits per spawner will appear as an inverse of the pattern of spawning biomass as annual rates of production have leveled off. For this reason, it is important to also consider recruitment, as well as recruits per spawning biomass. Recruit abundance of each species was lagged by the appropriate number of years to match the spawning biomass that produced them. For graphical display, the median of each time series was subtracted from the log-transformed recruit per spawning biomass ratios and expressed as a proportion of the median.

Generally, climate regime-scale variability in recruit per spawner time series was detected in flatfish and rockfish, but not in groundfish (pollock, cod, Atka mackerel, and sablefish) species (Figs. 105 and 106). The 1988/89 shift was apparent in all winter spawning flatfish species in the Bering Sea but not in the GOA. Shifts in other flatfish of the Bering Sea were not detected, except yellowfin sole which showed the 1976/77 shift. A shift in 1988/89 was detected in the

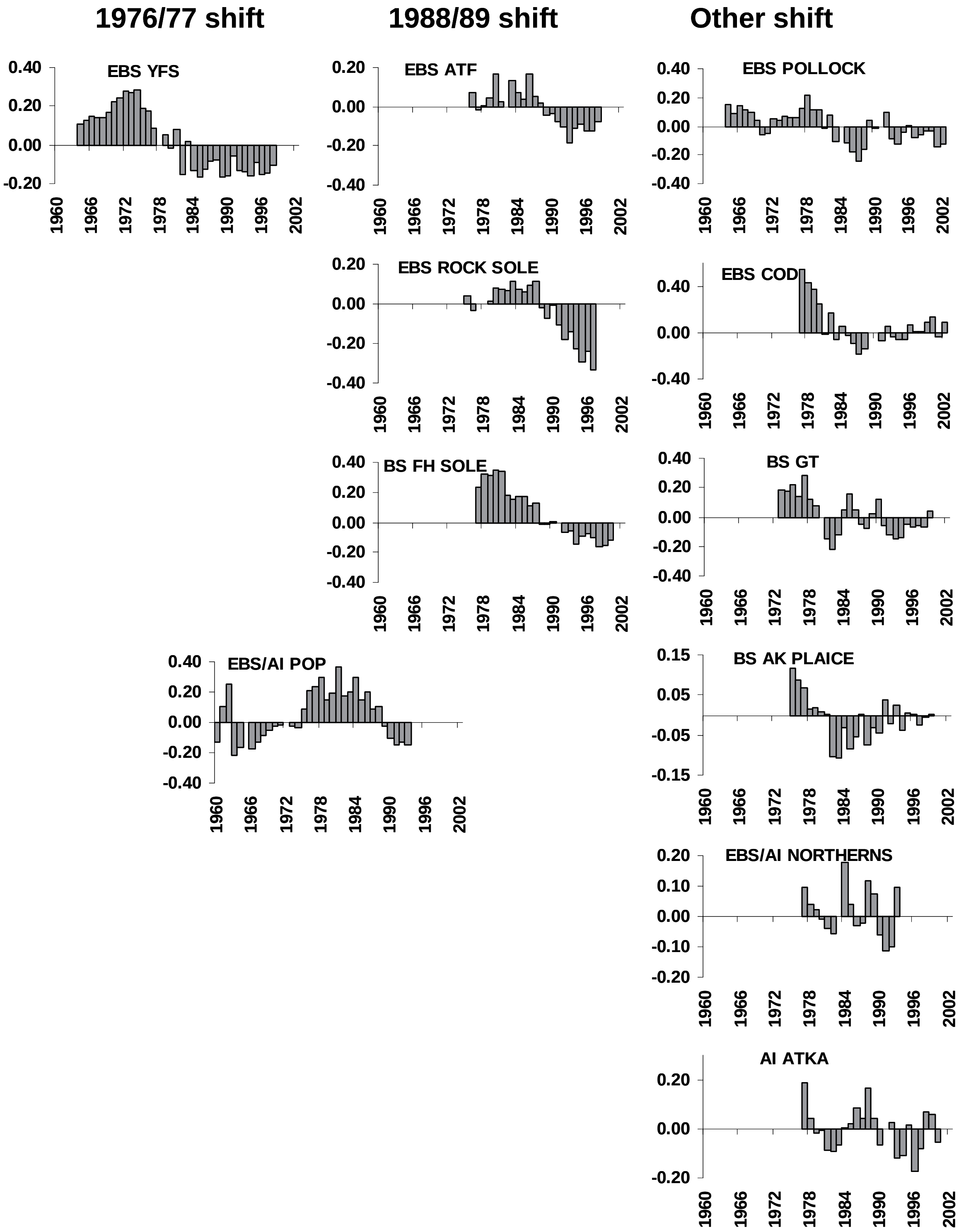

Fig. 105 Median recruit per spawning biomass anomalies for BSAI groundfish species assessed with age- or size-structured models from 1960 to 2002. EBS = Eastern Bering Sea, BS = Bering Sea, AI = Aleutian Islands, YFS = yellowfin sole, ATF = arrowtooth flounder, FH sole = flathead sole, POP = Pacific ocean perch, GT = Greenland turbot, Atka = Atka mackerel. Note that EBS/AI POP showed a shift in 1976/77 and 1988/89 (NPFMC, 2004, Appendix D).

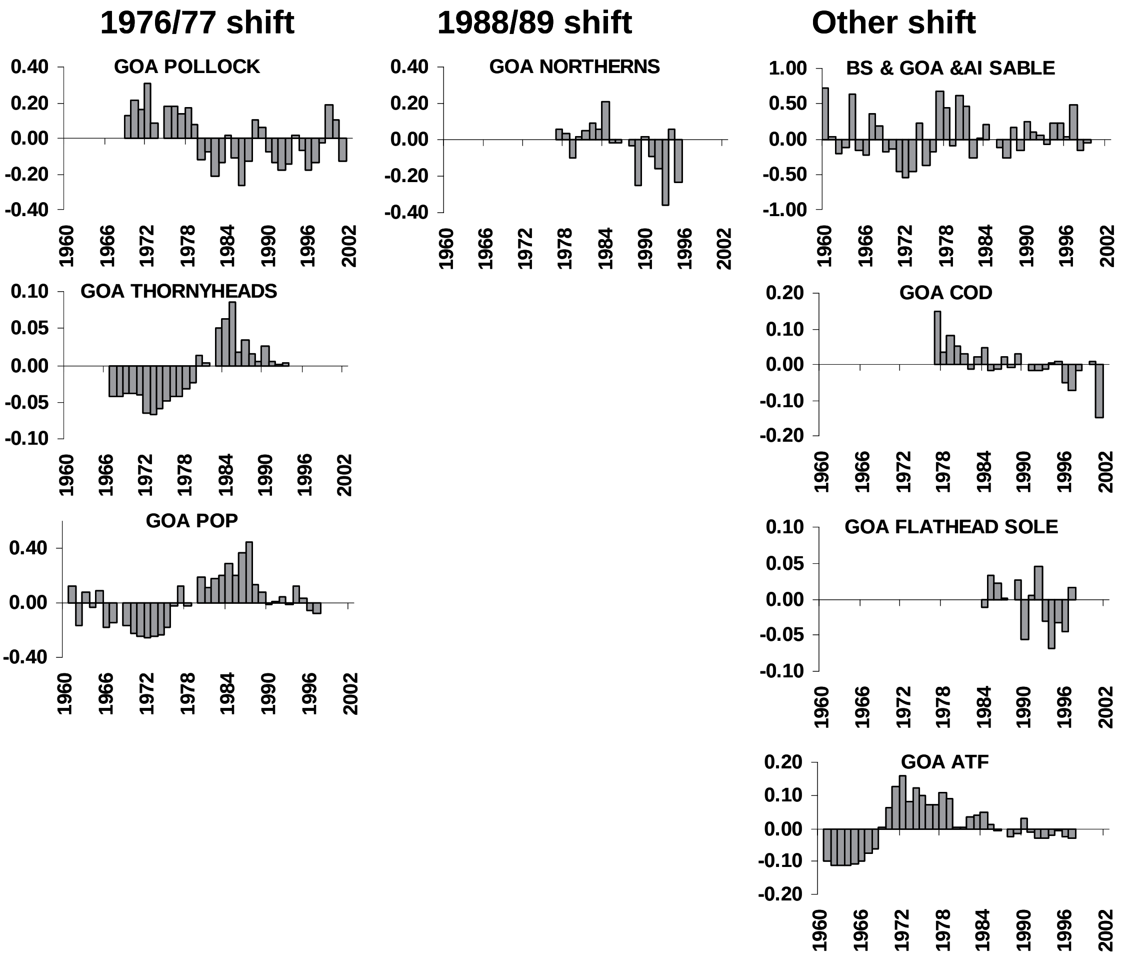

Fig. 106 Median recruit per spawning biomass anomalies for GOA groundfish species assessed with age- or size-structured models from 1960 to 2002. GOA = Gulf of Alaska, ATF = arrowtooth flounder, POP = Pacific ocean perch, Sable = sablefish (NPFMC, 2004, Appendix D).

survival of two rockfish species (EBS Pacific ocean perch (*Sebastes alutus*) and GOA northern rockfish (*S. polyspinis*)) and a shift in 1976/77 was detected in several rockfish species (EBS POP, GOA POP, and GOA thornyhead rockfish (*Sebastolobus* sp.). No shift was seen in the EBS northern rockfish time series. The effect of heavy fishing during the 1960s may have influenced the EBS POP recruit per spawner biomass ratios. Therefore, the analysis was performed on recruits to reduce this effect. The results of this analysis were the same as that for recruit per spawners, indicating that there was a shift in EBS POP survival in 1976/77 and 1988/89 (no shifts were seen in GOA POP recruits).

The results of a non-parametric change-point analysis suggest that a linear trend is the best fit model for most groundfish species, whereas a discontinuity model provided the best fit for most flatfish and rockfish species in the BSAI and GOA. Primary step changes in recruit per spawner time series were found for 12 of the 19 groundfish species, 6 of which were significant ($p < 0.05$). There were three general time periods in which step changes were detected: 1968, 1974–1979, and 1987–1992. Winter spawning flatfish step changes typically occurred from 1987 to 1992; most rockfish step changes occurred in the mid-1970s and 1980s.

The survival of groundfish does not appear to be related to decadal-scale climate variability, as defined by the hypothesized 1976/77, 1988/89, or 1998 years of regime shifts. Examination of the average recruit per spawning biomass anomalies, however, indicates that groundfish experience similar trends in survival within ecosystems. For example, pollock and cod have similar recruit per spawner trends in both the BSAI and GOA

(Fig. 107). Aleutian Islands pollock and Atka mackerel (not included in this analysis) also show similar patterns in recruitment (Fig. 107; Barbeaux *et al.*, 2003). This may be an indication that groundfish respond in similar ways to large-scale climate changes that are not defined by the years of hypothesized regime shifts or are not detected with the type of analyses conducted in this study.

Flatfish survival shows decadal-scale variability in survival. In particular, the BSAI winter spawning flatfish (rock sole, flathead sole and arrowtooth flounder) show a negative shift in survival for the late 1980s. Examination of the recruitment of winter-spawning flatfish in the Bering Sea, in relation to decadal atmospheric forcing, suggests favorable recruitment may be linked to wind direction during spring (Wilderbuer *et al.*, 2002). Years of consecutive strong recruitment for these species in the 1980s correspond to years when wind-driven advection of larvae to favorable inshore nursery grounds in Bristol Bay prevailed. The springtime wind pattern changed to an off-shore direction during the 1990s which coincided with below-average recruitment. Rockfish survival also appears to be related to decadal-scale variability, but the mechanism is unknown. Also, recruit per spawning biomass ratios are autocorrelated in long-lived species, such as rockfish. However, analyses on recruits showed similar results as those conducted on the recruit per spawning biomass ratios for EBS POP.

Flatfish

Swartzman *et al.* (1992) noted that the relationship between habitat use of EBS flatfish (as measured by catch per unit effort (CPUE) from summer trawl surveys) and temperature has generally remained constant over time. Paul Spencer (NPFMC 2004, Appendix D), however, examined the hypothesis that flatfish may shift distributions in order to maintain temperature preferences. Recent bottom temperatures in the EBS show considerable contrast and thus provide an opportunity to examine the relationship of flatfish distributions to temperature variability. For example, 1999 was one of the coldest years on record and a warming trend has occurred since 2000 such that 2003 was one of the warmest years observed. The average latitude and longitude, by year, of the survey stations within the "cold pool" (defined as water < 2°C) from the 1997 to 2003 EBS shelf survey is shown in Figure 108, as well as the annual centroids for individual species

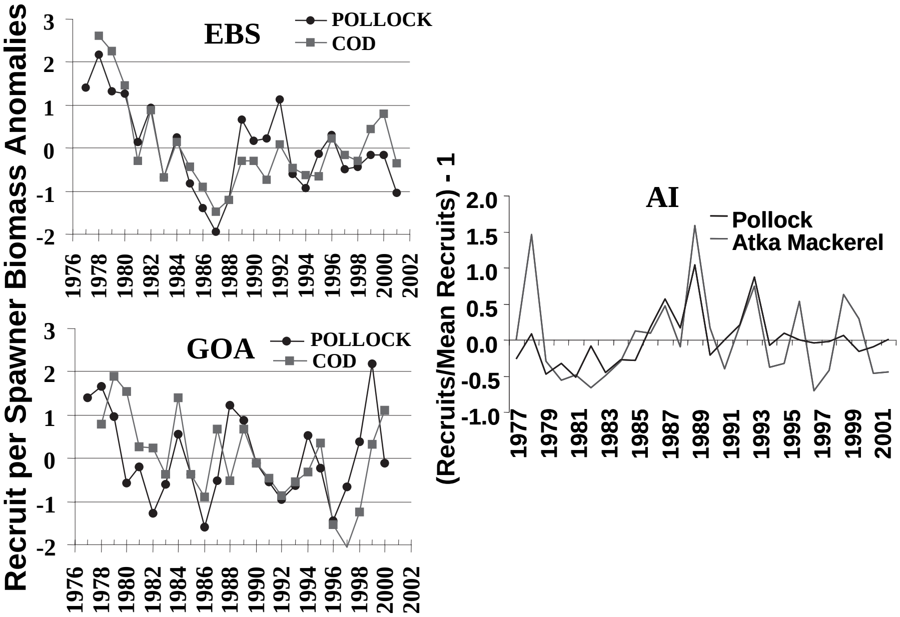

Fig. 107 Recruit per spawner anomalies of Bering Sea–Aleutian Islands (BSAI) and Gulf of Alaska (GOA) pollock and cod and Aleutian Islands pollock and Atka mackerel (lagged back 1 year) recruits expressed as a proportion of mean recruits. Atka mackerel spawn in the summer and pollock spawn in the winter. Therefore, the Atka mackerel were lagged by 1 year to match the year classes that experienced similar conditions (modified from Barbeaux *et al.*, 2003).

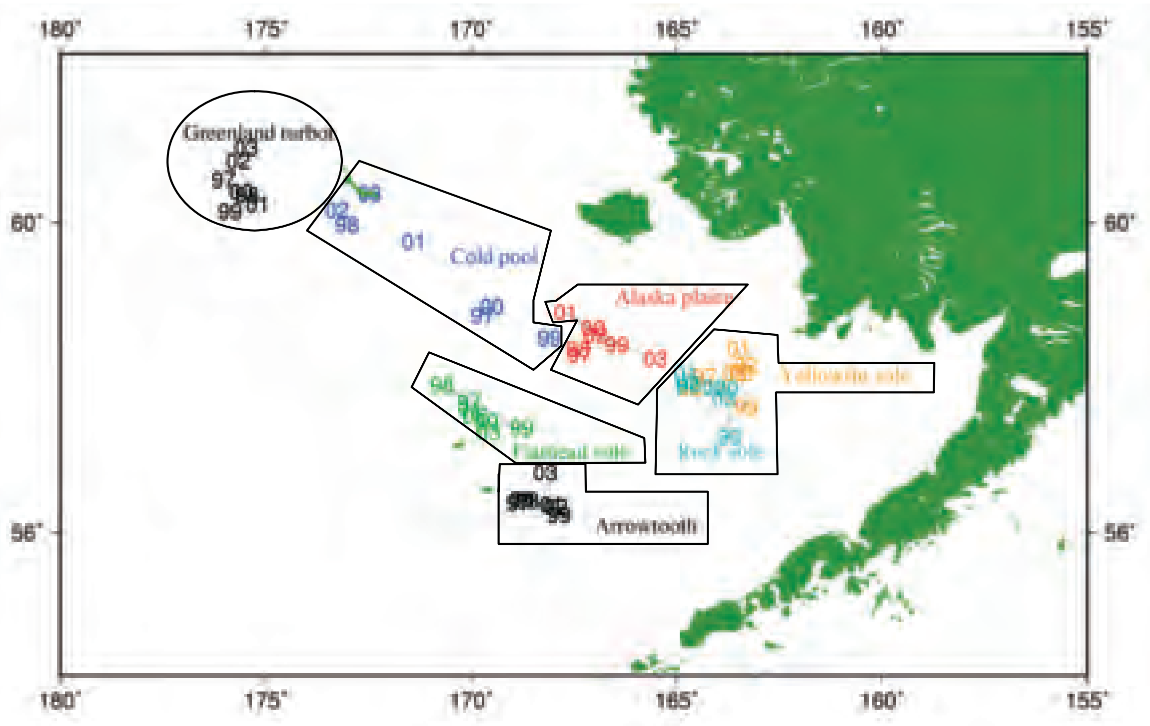

Fig. 108 Centroids of various flatfish species abundances and the cold pool in the eastern Bering Sea (EBS) from 1997 to 2003, as derived from summer bottom trawl surveys. Lines are drawn around the centroids and cold pool for visual display only (Spencer, NPFMC 2004, Appendix D).

(average latitude and longitude of survey stations containing a particular species, weighted by CPUE). From 1998 to 1999, the centroid of the cold pool moved to the southeast and was at its lowest latitude observed from 1982 to 2003. The warming trend since 2000 is revealed in the northwest movement of the cold pool centroid such that the 2003 centroid is at it highest latitude observed from 1982 to 2003.

The centroids of many flatfish populations, including yellowfin sole, rock sole, flathead sole, and arrowtooth flounder, also appear to have moved to the southeast in 1999, presumably in response to cold ocean conditions. Scaled time series (1982 to 2003) of the location of the cold pool and flatfish centroids follow along an axis running from the southeast to northwest EBS shelf (NPFMC 2004, Appendix D). Although most species do not show a significant statistical relationship to the location of the cold pool over the entire time series, the pattern of a southeast movement across several species in 1999 is observed in these time series. This finding suggests that flatfish habitat selection is related not only to seafloor characteristics, but is also influenced by water temperatures.

A significant relationship was found between the centroids of the cold pool and flathead sole from 1982 to 2003, indicating that flathead sole centroids are generally not found in the northwest during very cold years. The diet of flathead sole consists of a greater proportion of fish than other small flatfish, and one hypothesis is that flathead sole distributions may be linked to prey fish populations which, in turn, may be related to temperature. Alternatively, another hypothesis is that water temperatures in more northwestern areas of the EBS shelf may be outside the preferred temperature range for flathead sole during cold years. Additional research will be needed to investigate these hypotheses.

Pacific halibut (*Hippoglossus stenolepis*)

Fishery and biology

Pacific halibut are managed separately from other groundfish species in the BSAI and GOA. They have one of the longest histories of research and represent a bottom dwelling flatfish that may be better sheltered from extreme variations in climatic changes, at least after their early life history stages when the eggs and larvae drift with the currents. This species is found throughout the coastal waters of Alaska, British Columbia, Washington, Oregon and northern California. Their center of abundance is the central GOA, particularly near Kodiak Island. Depths for adults range from 50 m during summer feeding to 600 m during winter spawning. Pacific halibut are generally found in waters at temperatures from 3° to 9°C.

Pacific halibut begin to mature at approximately 8 years of age. During the spawning season, generally November to March, adults move to deeper waters near the edge of the continental shelf. Halibut are broadcast spawners. Their eggs and larvae drift in the surface currents for 6 to 7 months after spawning. During this long pelagic phase, halibut generally drift westward in the GOA and northward into the Bering Sea by the dominant surface currents before settling to the bottom in shallow waters in late spring and summer. It is at this long stage when extreme changes in climate are expected to have the greatest impact on the success of year classes, although in recent years, the relative distribution of recruited (*i.e.*, fish 8 years and older) halibut biomass by area remains relatively constant from year to year. To achieve migration continuity, juveniles migrate back to the south and east towards their spawning grounds. This counter-migration usually takes place between ages 2 and 6. Adults show seasonal migration (to deeper water for spawning) but very little directed migration.

A commercial fishery for halibut has existed since 1888. During the 20th century, landings ranged between 17,000 and 40,000 t. The current health of the fishery is generally good since some of the highest landings on record were taken in the last 5 years of the 1990s. Since 1995, the fishery has been managed under an Individual Transferable Quota system. In addition to the commercial fishery, there is a growing sport fishery, and halibut are also captured incidentally in other North Pacific groundfish fisheries.

Climatic influences

Climate variability has been shown to affect the life history and distribution of Pacific halibut. During the 20th century, there have been dramatic and persistent changes in the growth and recruitment of the species that cannot be readily explained by changes in stock size (Clark *et al.*, 1999). Over the last 15 years, the weight of individual halibut has decreased substantially, especially in Alaska (Fig. 109). For example, the modal animal in the Pacific halibut commercial catch, an 11-year-old female halibut landed in Kodiak, Alaska, averaged 40 lb (18 kg) weight in 1980. In 1995, the average weight for the same age female halibut was less than 20 lb (9 kg). Fifteen years ago fish of a given age were substantially larger in Alaska than in British Columbia; now there is no difference. In both respects, Pacific halibut growth is similar to what was observed in the 1920s and 1930s. An increase in weight occurred sometime during the 1940s, and the present decrease began in the mid-1970s. Fish are also maturing at a smaller size now than they used to, while the age at maturity is quite close to what it has always been, with 50% of females mature by age 11.

There have also been clear decadal variations in halibut recruitment and spawning biomass all through the century, or at least since about 1935 (Fig. 110). Most recently, there was a run of good year classes spawned in the late 1970s to at least the late 1980s. This kind of alternation has sometimes been viewed as a cycle, but could just as well reflect distinct periods of different environmental conditions. Recent work has strongly suggested that halibut recruitment is driven primarily by the PDO, an interdecadal mode of climate variability. Stock size on its own explains very little of the variability in recruitment. Much of the observed variation can be explained either by fitting separate stock recruitment curves to different periods, based on the PDO regimes, or by simply using the PDO as a covariate (Clark and Hare 2002, Fig. 111). The PDO has alternated between positive (productive for halibut) and negative (unproductive) phases every 25 to 35 years (Mantua *et al.*, 1997).

The influence of temperature on early Pacific halibut growth was examined by Hagen and Quinn (1991). They found that warmer temperatures were related to an increase in growth rate for the first few years of life. After about age 3, however, growth rate was influenced more by year-class strength, which they suggested might be due to density-dependent effects. They also suggested that early growth rate was a factor in determining year-class strength. Clark and Hare (2002) demonstrated the decrease in growth rates of the late 20th century followed the sharp increase in stock size, and were most likely a density-dependent response. They found no environmental influence on growth rates of fish ages 8 and older.

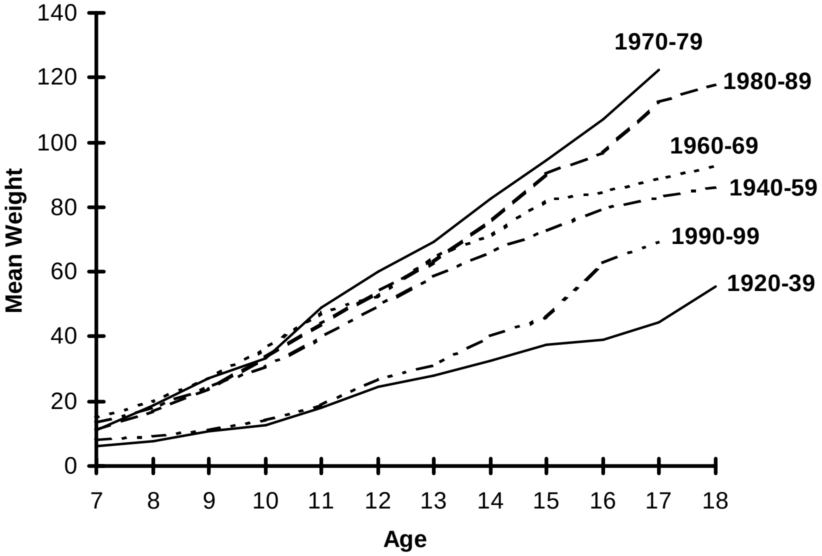

Fig. 109 Changes in mean weight (pounds) at age of female Pacific halibut in Alaska from 1920 to 1999.

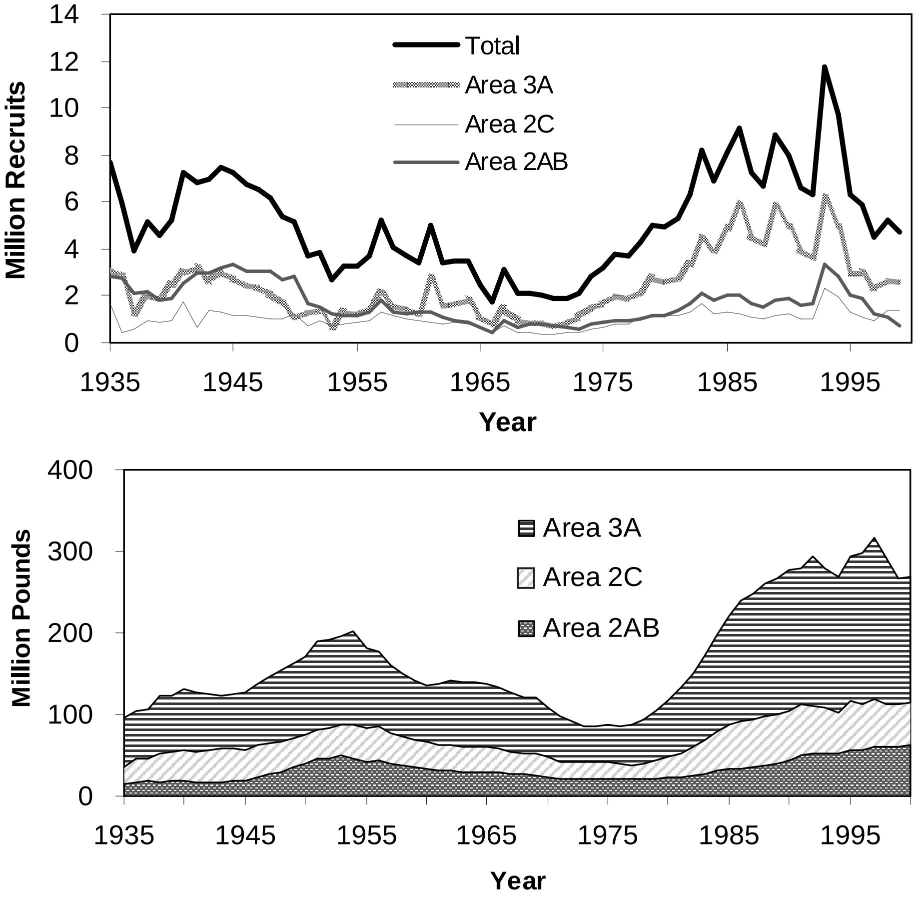

Fig. 110 Long-term trends in recruitment (measured as 6-year olds) and spawning biomass of Pacific halibut from 1935 to 2000, for International Pacific Halibut Commission (IPHC) areas 2AB (British Columbia), 2C (southeast Alaska), and 3A (central Gulf of Alaska).

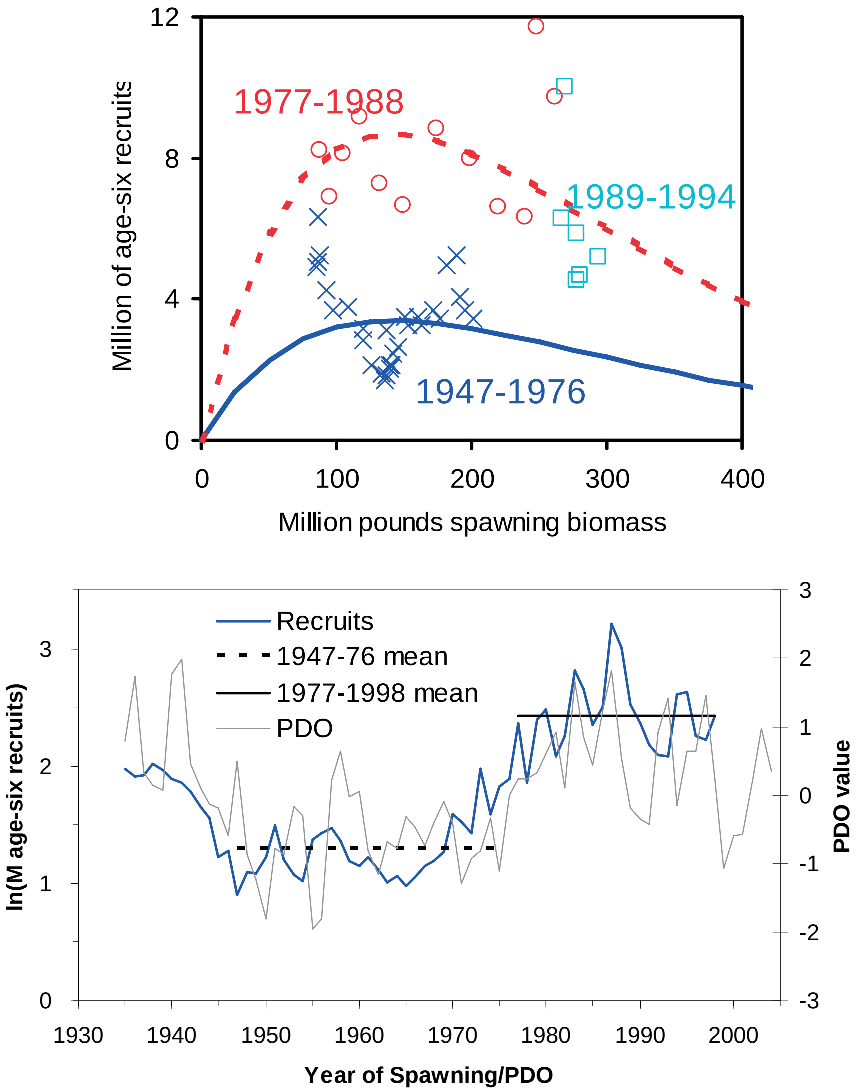

Fig. 111 Relationship between Pacific halibut spawning biomass and recruitment (top) and winter values of the Pacific Decadal Oscillation (PDO) and recruitment (bottom).

Climate variability impacts on Pacific halibut have mostly concerned the role of ocean temperature. Research to date suggests that warmer temperatures not only affect early growth rates and year-class size but may also have led to a shift in the distribution of Pacific halibut. Clark and Hare (2002) note that during the recent positive PDO regime (1977–1998), Pacific halibut recruitment to Alaska was substantially greater than it was in the earlier positive regime (1925–1946), whereas in British Columbia, recruitment was about the same, or a bit less, than the earlier positive regime. They speculate that this may be a manifestation of warming, as the waters of the North Pacific have warmed over the 20th century and thus may have shifted the optimal temperature range (3°–9°C) to the north.

Pacific halibut population abundance is related to conditions established in the upper ocean water layer which result from climate influences, including the PDO, ENSO, and local climate. The mechanisms determining survival are believed to be operative in the initial year of life, likely during the first several months following spawning. The pelagic phase of Pacific halibut lasts 6 to 7 months during which time the eggs and larvae are transported around the Alaska Gyre before settling on the continental shelf from the central GOA to the Bering Sea and along the Aleutian chain. Transport distance is linked to the rotational speed of the gyre which can vary on inter-annual and inter-decadal time frames. Survival of larval and juvenile halibut is intimately tied to the ecological and oceanographic conditions in the near surface waters during the pelagic phase.

Shellfish

Crab

Fishery

Crab resources are managed primarily by the Alaska Department of Fish and Game. Three king crab species, red (*Paralithodes camtschatica*), blue (*P. platypus*) and golden or brown (*Lithodes aequispina*), and two Tanner crab species, Tanner crab (*Chionoecetes bairdi*) and snow crab (*C. opilio*), have traditionally been harvested commercially off Alaska. As abundances have declined, exploratory fisheries on new deep-water stocks of scarlet king crab, grooved Tanner crab, and triangle Tanner crab have begun, producing only minor landings to date. Information on current and long-term potential yield is lacking for king and Tanner crabs. Thus, default values are derived from historical average landings. Long-term potential yield is represented by catch averages; current potential yield is set equal to recent average yield, calculated as the most recent 3-year average. The recent average yields for king (8,130 t), snow (13,038 t) and Tanner (712 t) crabs are below their respective long-term potential of 36,481, 37,202 and 21,751 t, respectively. The harvest of snow crab has been lower than the long-term potential since 2000 due to low abundance and lower harvest rates established under a rebuilding plan. Catches of crabs are restricted by quotas, seasons, and size and sex limits, with landings limited to large male crabs. Fishing seasons are set at periods of the year to avoid molting, mating, and soft-shell periods, both to protect crab resources and to maintain product quality.

Catch trends for king crabs are shown in Figure 112. Until 1967, Japanese and Russian fisheries dominated Bering Sea landings, but those fisheries were phased out by 1974. In the Bering Sea, domestic catches peaked at 74,000 t in 1980 and then dropped precipitously in 1981. Since then, the catches have remained low. GOA catches peaked in 1965 (Fig. 112), then varied at a relatively low level for a decade before dropping lower still in 1983. Almost all GOA king crab fisheries have been closed since 1983.

Tanner crab catch trends (Fig. 113) show that the 1965–1975 period was a developmental phase for the fisheries. The catch peaked in 1979 and then declined to 1984. After 1984, the catch increased, reaching an all-time high of 168,000 t in 1991, and then decreased to 1997, when the Tanner crab fishery was closed. Abundance trends for Bering Sea stocks indicate that the Tanner crab stock declined from a relatively high level in the late 1970s to a low level in 1985. The stock recovered and then declined again subsequent to 1989, and is currently at a low level. Snow crab rebounded sharply, from a low level in 1985, producing large catches in the 1990s, and then declined in 1999 to low levels. Snow crab catch decreased from 2000 to 2003 due to low abundance (figure not shown).

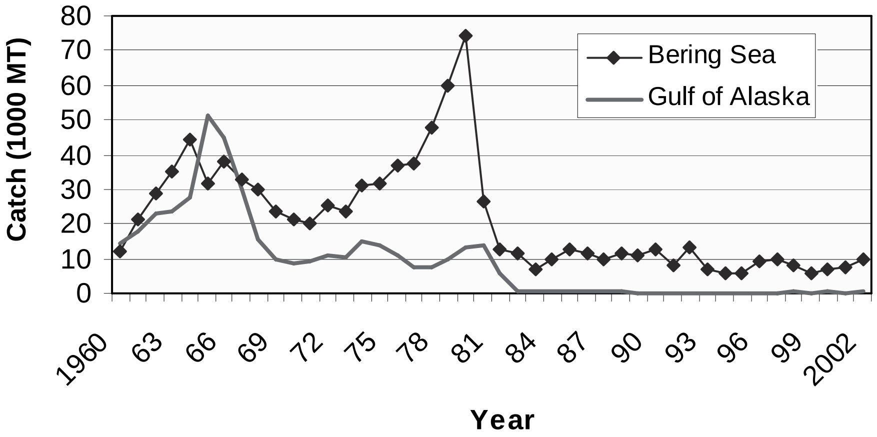

Fig. 112 Catch trend of Alaska king crab fisheries from 1960 to 2003.

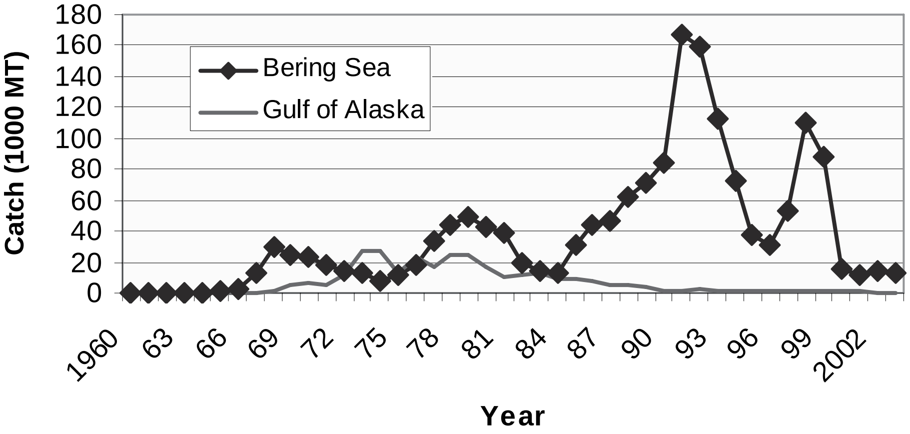

Fig. 113 Catch trend of Alaska Tanner crab fisheries from 1960 to 2003.

Abundance

Abundance of EBS crabs is determined using an "area-swept" method in a stratified systematic sampling design in an annual NMFS trawl survey (NPFMC 2004, Appendix D). Current abundances are low (Fig. 114), and of the six crab fisheries included in the Fishery Management Plan, two are open, four are closed, and four are considered overfished.

Bristol Bay red king crab

The mature biomass of Bristol Bay red king crab was highest in 1980, declined, and has remained relatively low since 1983. The total mature biomass of crabs has remained above 50% of the maximum sustainable yield (MSY) biomass and, therefore, the stock is not considered overfished. Abundance of legal and pre-recruit males increased by 10% in 2004 whereas the number of mature females decreased by about 9%.

Pribilof Islands red king crab

The mature biomass of the Pribilof Islands red king crab was well below 50% MSY in the 1980s but has been higher than the 50% MSY since 1991 and is not considered overfished. Apparent abundance of large male crabs decreased by about 62% in 2004 while that of mature females decreased by about 62%. No pre-recruit males were captured. Although not considered overfished, the fishery remains closed because of considerable uncertainty regarding population abundance, and due to concerns of unacceptable levels of incidental catch of severely depressed blue king crab in the same district.

Pribilof Islands blue king crab

Blue king crab in the Pribilof Islands area have been considered overfished since the mature biomass fell below the 50% MSY in 2002. Abundance of mature biomass continued to decrease in 2004 and is now the lowest on record. Little or no recruitment is apparent in the population which has been declining continuously since 1995. Continued warm conditions in the surrounding waters may be contributing to the decline.

St. Matthew Island blue king crab

Blue king crab in the area of St. Matthew Island are also considered overfished. The population has declined steeply since 1998. Legal and pre-recruit male abundances decreased by 11 and 33%, respectively, in 2004. Indices of female crab abundances are not considered meaningful due to their preference for inshore and rocky untrawlable habitat.

Eastern Bering Sea Tanner crab

The eastern Bering Sea Tanner crab population was high in the early 1980s and from 1988 to 1992. The population has been low since then and currently continues to decrease due to low recruitment. The mature biomass is below 50% MSY; therefore, the stock is considered overfished and the fishery has been closed since 1996. In 2004, the abundance indices for legal males (–28%) and mature females (–29%) decreased, while that of pre-recruit males increased (+25%).

Eastern Bering Sea snow crab

The mature biomass of eastern Bering Sea snow crab was moderate to high in the early 1980s and from 1987 to 1997. The biomass has declined sharply from 1998 to 1999 and the stock is considered overfished. In 2004, the abundance index for commercial-sized males (+2%) and pre-recruit males (+3.6%) increased slightly, while that for mature females increased more substantially (+25%). A small fishery (about 9,500 t) was allowed in January 2005 under the terms of the rebuilding plan.

Snow crab recruitment was higher during 1979–1987 than in other years (Fig. 115). The two highest recruitment events occurred in 1980 and 1987, after which recruitment was low. Low recruitment estimates since 1988 could be due to fishing, climate, and/or a northward shift in snow crab distribution. A northward shift in distribution could result in a decrease in reproductive output because snow crab may only spawn every other year (rather than annually) in colder temperatures, such as those found farther north.

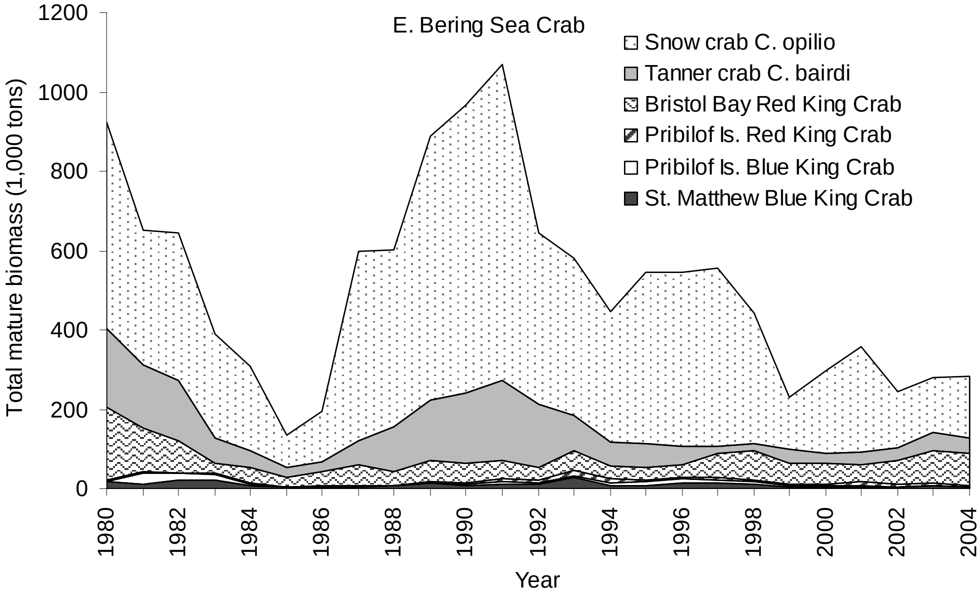

Fig. 114 Total mature biomass of eastern Bering Sea (EBS) crab populations from 1980 to 2004 (NPFMC 2004, Appendix D).

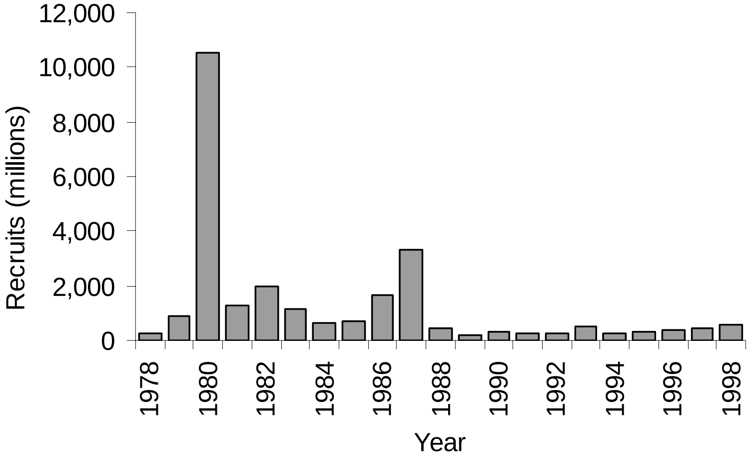

Fig. 115 Snow crab recruitment from 1978 to 1998 in millions of crabs that are 25 to 50 mm in carapace width and lagged by 5 years (to fertilization year) (NPFMC, 2004, Appendix D).

Climatic influences

Stock-recruitment relationships for Bristol Bay red king crabs

Jie Zheng of the Alaska Department of Fish and Game (NPFMC 2004, Appendix D) developed the spawner–recruit (S-R) relationships for Bristol Bay red king crabs using a length-based model. He reported that, in general, strong recruitment occurred with intermediate levels of effective spawning biomass, and very weak recruitment was associated with extremely low levels of effective spawning biomass. These features suggest a density-dependent S-R relationship (Fig. 116). On the other hand, strong year classes occurred in the late 1960s and early 1970s, and weak year classes occurred in the 1980s and 1990s. Therefore, recruitment is highly autocorrelated, so environmental factors may play an important role in recruitment success. The general Ricker curve (R^2 = 0.53) was used to describe the density-dependent relationship and the autocorrelated Ricker curve (R^2 = 0.45) was used to depict the autocorrelation effects. The recruitment trends of Bristol Bay red king crabs may relate partly to decadal shifts in physical oceanography: all strong year classes occurred before 1977 when the Aleutian Low was weak. The largest year class during the last 20 years, the 1989 brood year, was also coincidental with the weak Aleutian Low Pressure Index (ALPI) during 1989–1991.

Major climate indices and recruitment variation of Eastern Bering Sea crabs

Most crab population fluctuations off Alaska are caused by recruitment variability. The variability is expected at the greatest magnitude during the egg and larval stage when survival of the crabs is at the mercy of the currents. Zheng and Kruse (2006) examined the effects of four environmental factors on six crab stocks in the EBS (Fig. 117) that would have a strong impact on the ocean conditions, ALPI, PDO, proportion of ice coverage, and near-bottom temperatures. They compared the trends of crab recruitments and these climate indices. The ALPI and PDO showed similar trends, which are opposite to that of the ice coverage index (Fig. 118). All these indices exhibit decadal-scale variability. Among the six crab stocks in the same general vicinity of the eastern Bering Sea shelf area, Bristol Bay red king crab recruitment trends appeared to relate best to decadal shifts in physical oceanography: all strong year classes occurred before 1977 when the Aleutian Low was weak. The largest year class during the last 20 years, the 1990 year class, was also coincidental with the weak ALPI during 1989–1991. Specific mechanisms linking Bristol Bay red king crab recruitment and the physical oceanography are unclear. Zheng and Kruse (2000) hypothesized that the Aleutian Low strength affected food availability for red king crab larvae. They stated that strong Aleutian Lows may have adverse effects on species composition of the spring bloom for red king crab larvae. Diatoms, such as *Thalassiosira*, are important food for first-feeding red king crab larvae (Paul *et al.*, 1989), and they predominate in the spring bloom in years of light winds when the water column is stable (Ziemann *et al.*, 1991). Years of strong wind mixing associated with intensified Aleutian Lows may depress red king crab larval survival and subsequent recruitment. Yet, the recruitment trends of other crab stocks cannot be consistently explained by the decadal-scale variability of these environmental data. It is possible that red king crabs in Norton Sound are too far north to be significantly affected by the Aleutian Low dynamics.

Water temperature is an obvious climatic index that would affect development and survival of recruitment and growth of crabs. Rosenkranz *et al.* (1998, 2001) reported on recruitment variations for Tanner crab stocks in the EBS as they relate to (1) warm bottom temperatures which favor Tanner crab gonadal development and egg incubation, and (2) warm sea surface temperatures. Warm sea surface temperatures during spring promote increases in *Pseudocalanus* copepod nauplii, a primary prey of Tanner crab larvae, thus favoring feeding success of Tanner crab larvae due to higher prey densities. Statistically significant correlations exist between Tanner crab year classes and these temperatures (Rosenkranz *et al.*, 1998, 2001).

Zheng and Kruse (2006) noted that most of the six different crab stock recruitment time series in the same general vicinity of the EBS are not significantly correlated with each other. As shown in Figure 117, the most closely related recruitment series are two blue king crab stocks. Norton Sound red king crab recruitment was also negatively related to the recruitment of two blue king crab stocks, however, explanatory mechanisms for such relationships are unclear. Thus the authors observed that “if large-scale physical forcing affects these stocks, they may not affect each stock the same way, as suggested by poor correlations among the stocks.”

Since recruitment variations are also strongly related to spawning biomass, competition and predation, the authors have, in separate studies, examined all these other factors which would impact survival and recruitment of crabs. Zheng and Kruse (2003) found that spawning biomass explained only a small portion of recruitment variation for crab stocks in the EBS. In another study, Zheng and Kruse (2006) found that some empirical evidence supports speculation that groundfish predation may play an important role in crab recruitment success in the EBS. However, spatial dynamics in the geographic distributions of groundfish and crabs over time make it difficult to relate crab recruitment strength to groundfish biomass.

In the end, the authors observe that "no single factor alone can consistently explain crab recruitment variation in the EBS, in part because most crab stocks in the same general vicinity, like the eastern Bering Sea, have divergent recruitment patterns." This observation emphasizes the difficulty of predicting how ocean warming would impact crab survival and recruitment.

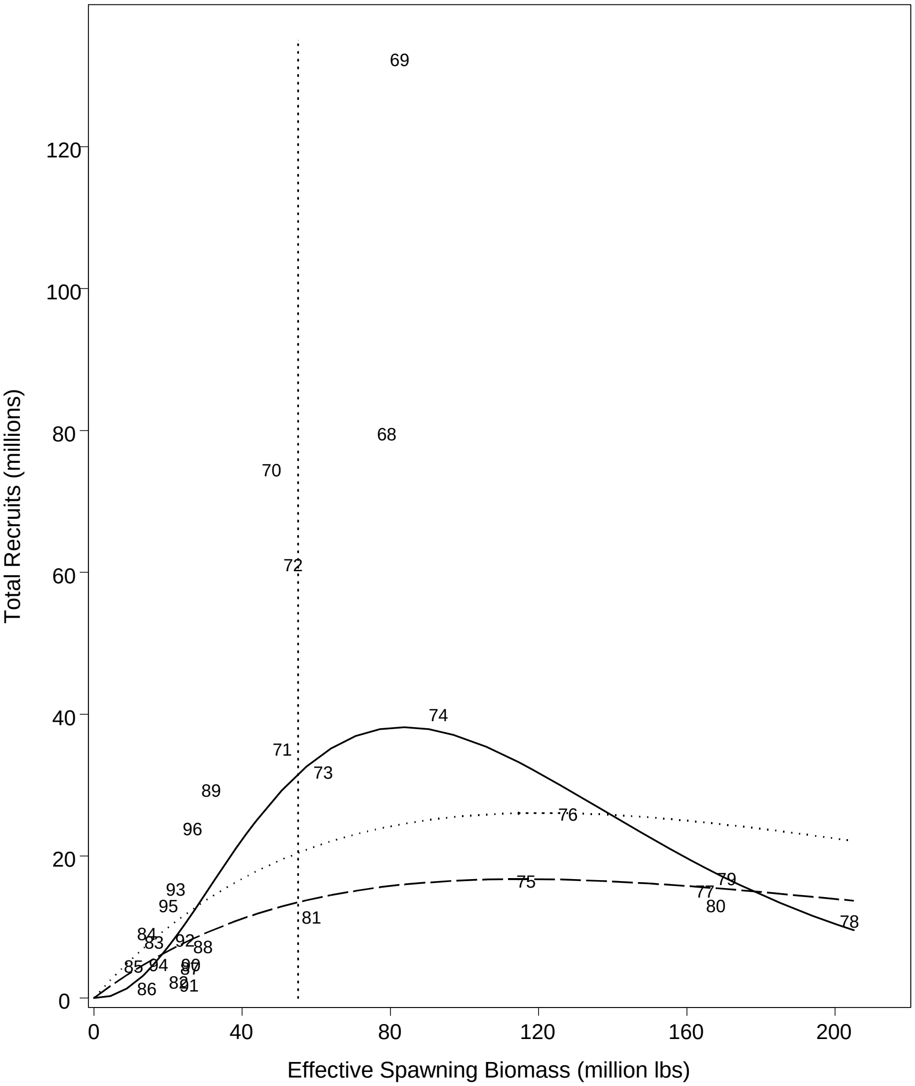

Fig. 116 Spawner–recruit relationship of Bristol Bay red king crab. The recruitment trends of Bristol Bay red king crabs may relate partly to decadal shifts in physical oceanography: all strong year classes occurred before 1977 when the Aleutian Low was weak. The largest year class during the last 20 years, the 1989 brood year, was also coincidental with the weak Aleutian Low Pressure Index during 1989–1991 (from Zheng and Kruse, 2003).

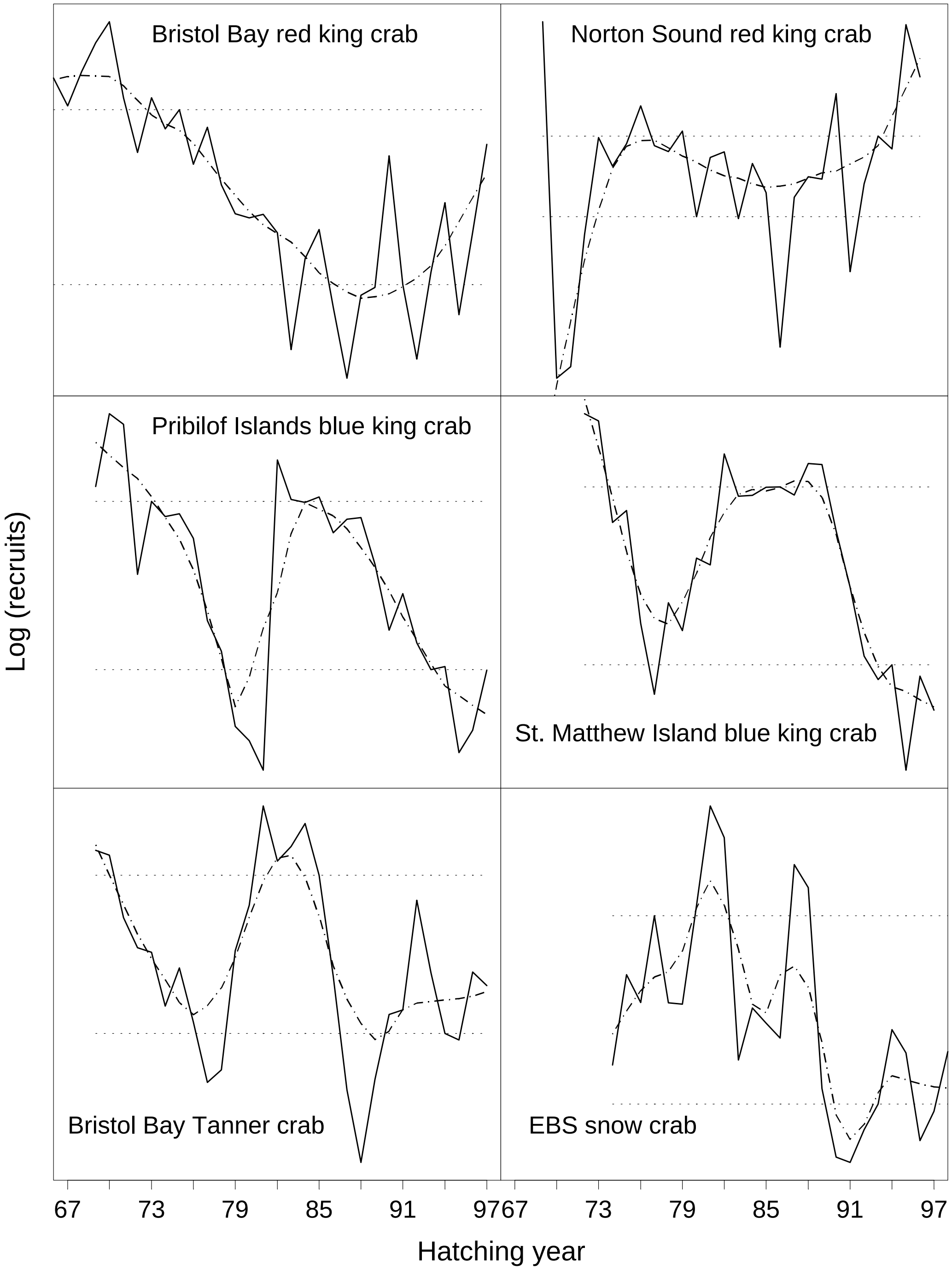

Fig. 117 Time series of log-transformed recruitment (solid line) for six crab stocks in the eastern Bering Sea. Dashed lines are LOWESS smoothed lines, and dotted lines are limits for the 25% lower and upper quartiles of recruitment (from Zheng and Kruse, 2006).

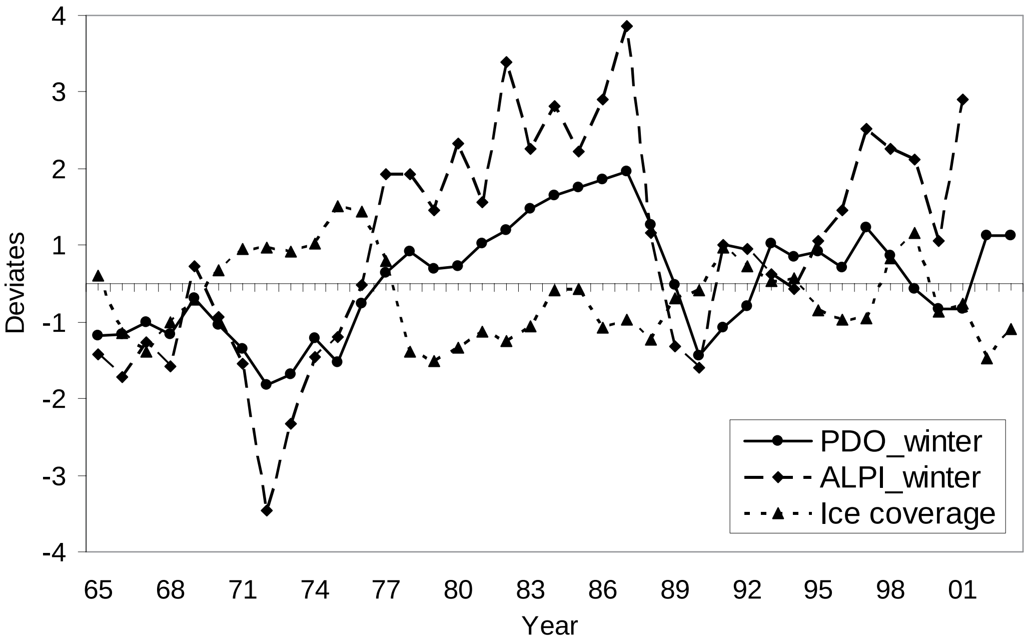

Fig. 118 Time series anomalies for three major climatic indices in the eastern Bering Sea: the winter Aleutian Low Pressure Index (ALPI), the December–March Pacific Decadal Oscillation (PDO) Index, and Bering Sea ice coverage index. All indices are 3-year running averages (from Zheng and Kruse, 2006).

Change in crab spatial distributions and implications on the role of advection on crab recruitment

Zheng and Kruse (2006) analyzed changes in spatial distributions of crab abundance in the EBS and how they might be related to the regime shifts during the last 30 years. The excerpts below highlight the results of their analyses. They found the spatial distribution of red king crab in the EBS had changed profoundly during the last three decades (Fig. 119). Female red king crabs were found primarily in central Bristol Bay during 1980–1987 and 1992–2004. The distribution centers (centroids) of mature females moved south slightly during 1988–1991 but did not reach the southern locations previously occupied in the 1970s. Small immature females occurred primarily along the shore and in northeastern Bristol Bay, and mature females occurred in the deeper water and offshore. With ontogeny, young red king crab tend to move from inner Bristol Bay in a southwesterly direction along the north shore of the Alaska Peninsula to central or southern Bristol Bay as mature females.

Centroids of Tanner crab in the EBS were highly variable during the past 30 years (Fig. 119), but only one pattern emerged. From 1978 to 1983, most females and the centroids for mature females occurred primarily west of the Pribilof Islands. From 1984 to 1986, a low abundance period, female crabs were evenly distributed throughout their geographic range. From 1987 to 1991, female Tanner crabs were concentrated within Bristol Bay. Few crabs were found in northeastern Bristol Bay from 1992 to 2004. Generally, small immature female Tanner crabs were located in waters deeper than for mature females. The spatial distribution of female snow crabs also changed over time (Fig. 119). It appears that the centroids of mature females have moved gradually to the northwest since the 1970s.

Zheng and Kruse (2006) state that the shifts of distributions for large mature female red king crabs in Bristol Bay occurred right after the 1976/77 regime shift, while the shifts of mature female snow crab occurred from the mid-1970s to the early 1980s. Loher (2001) hypothesized that changes in near-bottom temperatures associated with the 1976/77 regime shift were causes for spatial shifts of red king crab female distributions, and Orensanz *et al.* (2004) proposed a similar hypothesis to explain spatial changes for snow crab. Orensanz *et al.* (2004) further explained that the lagged northward shift of mature females, associated with warming during the 5-year period 1975–1979, was indicative of a corresponding northward shift in larval settlement. Both studies attributed spatial shifts of crab distributions to the cold pool in the early and mid-1970s and subsequent high near-bottom temperatures in the late 1970s and early 1980s. During the late 1970s and early 1980s, when near-bottom temperatures were very high, the centroids of mature female Tanner crab were primarily west of the Pribilof Islands (Fig. 119), and few female Tanner crabs were found in central Bristol Bay after the regime shift in 1989.

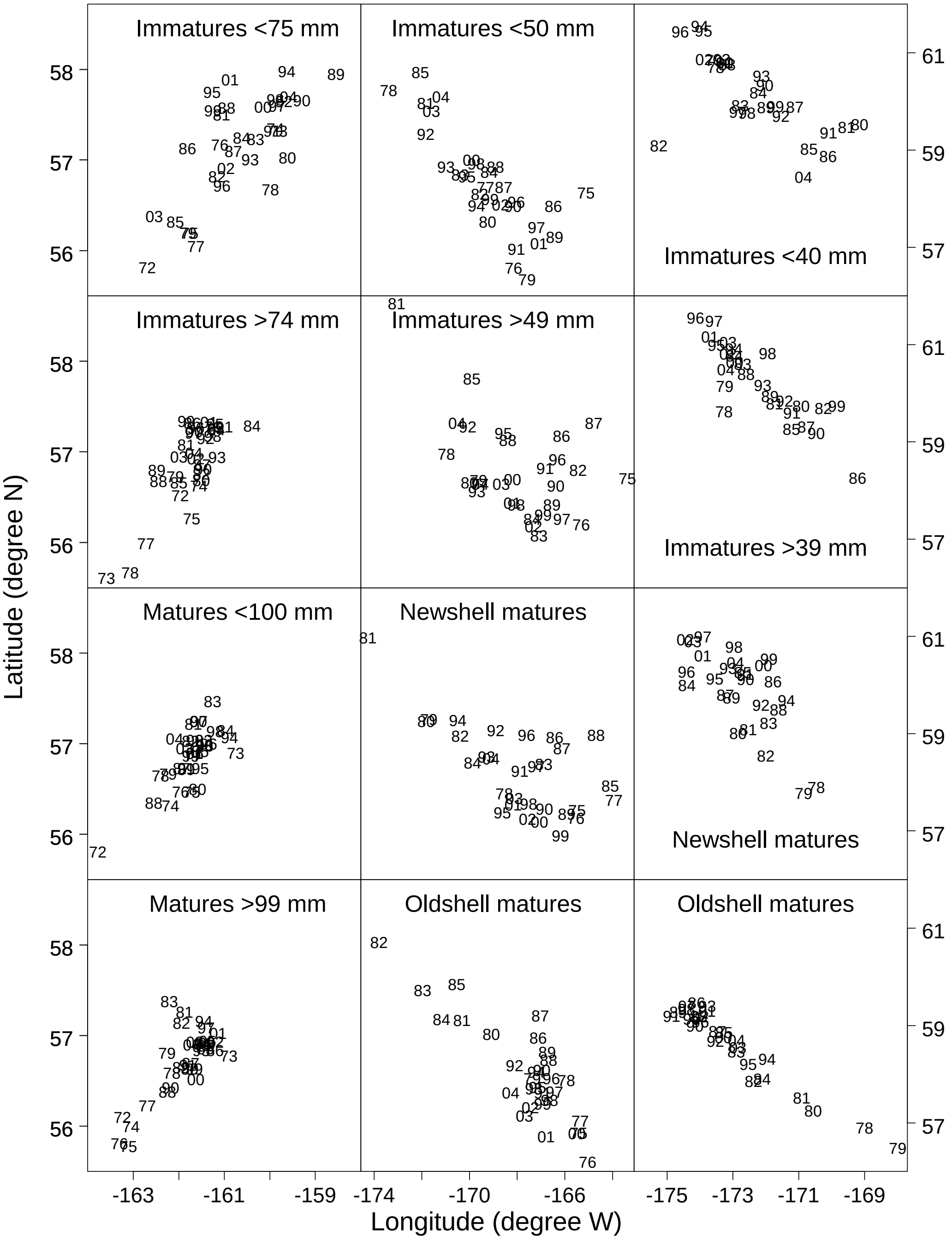

Fig. 119 Distribution centers of female abundance for Bristol Bay red king crab and eastern Bering Sea Tanner and snow crabs. The left *y*-axis is for red king and Tanner crabs, and the right *y*-axis is for snow crab (from Zheng and Kruse, 2006).

Overall, after the regime shift in 1976/77, EBS crab stocks have been stronger in the northern than in the southern habitats. For two red king crab stocks, the northern stock (Norton Sound) has recovered better from previous lows during the last 15 years than has the Bristol Bay stock. Within the Bristol Bay stock, the southern component has almost disappeared, whereas the northern component is rebuilding. For two blue king crab stocks, the mature abundance of the St. Matthew Island stock (northern stock) was relatively high until 1999 whereas the Pribilof Islands stock has been depressed since the early 1980s (Vining and Zheng, 2004). The abundance of mature female snow crab has been extremely low in their southern range during the last 10 years.

Spatial distributions of mature and small juvenile female Tanner crab mostly overlap, with the distribution centers of juveniles generally being southwest of those of the mature females, whereas distribution centers of small juvenile red king and snow crabs are generally located downstream of the mature females. For Tanner crab spawners near the shelf edge, their larvae may be retained and may settle near the adults or be carried away by currents to areas with poor habitats. Thus, advection appears to be an important process for red king and snow crabs, whereas, in general, retention might be more favorable to the shelf-edge Tanner crab population.

Northward shifts and different spatial distributions of mature and juvenile females may partly explain the recruitment variation for Bristol Bay red king crab and EBS snow crab. The shifts of spatial distributions of mature females make it difficult to supply larvae to the southern ranges of their spatial distributions. This not only reduces the number of suitable habitats to which larvae are delivered (Armstrong *et al.*, 1993; Loher, 2001), but also slows juvenile growth due to relatively low temperatures in the north (Stevens, 1990), thus affecting recruitment strength.

Unlike red king and snow crabs, EBS Tanner crab nursery areas occur offshore on soft bottom sediments. For larvae released offshore, retention may be favorable, but for those released along the Alaska Peninsula, advection helps them to reach their nursery areas. Rosenkranz *et al.* (1998, 2001) showed that Tanner crab recruitment may be enhanced by northeast winds during the larval period. Winds blowing from the northeast along the Alaska Peninsula during spring (May and June) promote coastal upwelling (perhaps favoring productivity) while advecting larvae offshore to their nursery areas.

Pandalid shrimp

Shrimp (*Pandulus* and *Pandalopsis* spp.) were a prominent, commercially harvested resource in the Being Sea in the early 1960s but they were rapidly depleted due to overfishing and other environmental changes (NMFS, 1999). Environmental change must have affected this resource greatly, as shrimp biomass decreased significantly throughout Alaska, even when fishery exploitation levels were low. The abundance declined so quickly that this resource was not commercially harvested for 20 or more years, except in specialized areas. Thus, shrimp may be an indicator resource for the effects of ocean warming and associated climatic events.

The northern shrimp (*Pandalus borealis*) are the most important of the five species making up Alaska shrimp landings. The domestic shrimp fishery in western Alaskan waters is currently at a low level. Shrimp abundance is also too low in the Bering Sea to support a commercial fishery. The western GOA has been the main area of operation. During the 1970s, when the fishery was more productive, 50 to 100 vessels trawled for shrimp at Kodiak Island and along the Alaska Peninsula.

Shrimp landings in the western GOA (Fig. 120) show that catches rose steadily from 1965, peaked to about 58,000 t in 1976 and then declined precipitously to 2,000 t in 1984, and have remained at such low levels since; almost all of the landings came from southeastern Alaska. Bering Sea shrimp catches by Russia and Japan peaked at 32,000 t in 1963, declined gradually until the fishery ended in 1973. As with crabs, the potential yields of shrimp stocks in Alaska are not well understood, and have been equated to average catches. Shrimp stocks are managed by regulating catch levels according to stock abundance. In addition, spring “egg hatch” closures are used to protect breeding stocks.

Climatic influences

The life history and ecology of shrimp seems to be particularly susceptible to ocean and climatic conditions. Such influences are probably strong because climatic changes affect a broad phase of shrimp life history. Pandalid shrimps occupy a central position in the trophic structure of the northeastern Pacific, where they constitute the main prey of many fish species and, in turn, prey on the zooplankton community. They also occupy all depths of the water column from the benthos to near surface. Consequently, changes in their abundance and population dynamics directly reflect changes occurring within other trophic levels throughout the water column. The proportions of shrimp in survey catches were found to be negatively correlated (r = –0.72) with water column temperature (Anderson, 2000). Climate change, as manifested by changes in water column temperature, has an immediate effect on the lower trophic levels of boreal marine ecosystems, and rapid pandalid shrimp population changes are one of the first indicators that community structure is changing.

Abundance of all pandalid shrimp, estimated from trawl surveys in the GOA, shows dramatic declines from 1973 to 1988, with some signs of recovery in the late 1990s (Fig. 121). However, present abundance has still been substantially below those of the early 1970s. Shallow water species, *Pandalus goniurus* and *P. hypsinotus*, are restricted to only a few sampled locations, but showed increases in overall abundance in 2001. These species have, again, shown signs of declining abundance in 2003. *Pandalus goniurus* declined from 8 kg km^{-1} in 2001 to 1 kg km^{-1} in 2003. *Pandalus hypsinotus* has declined to less than 0.01 kg km^{-1} in the 2003 overall catch rate. Species with a greater depth distribution, *P. borealis* and *Pandalopsis dispar*, are showing declines in abundance but not to the degree of the shallow water species.

Analysis of length–frequency data from the various populations has provided clues to the mechanism responsible for the recent rapid population recovery. Strong size modes were evident in 2001 and 2002 (Anderson, 1991). Strong year classes of *Pandalus borealis* produced in 1999 and 2000 are directly responsible for the greater abundance of shrimp observed in the 2001 and 2002 surveys. Weak recruitment of young age groups since 2002 has resulted in lower abundance observed for the 2003 survey. Results indicate that shrimp may be good indicators of the current state of the marine environment in the GOA.

Recent changes in shrimp populations are directly linked to colder conditions, as indicated by PDO patterns. Sustained strong recruitment of pandalid shrimp will require a continued shift to colder ocean conditions (Anderson, 2000). Along with favourable oceanographic conditions to allow strong recruitment of shrimp, there will also need to be declines in predation pressure. These principle factors play a central role in determining future pandalid population trends, and governing trends in other species abundance, as well.

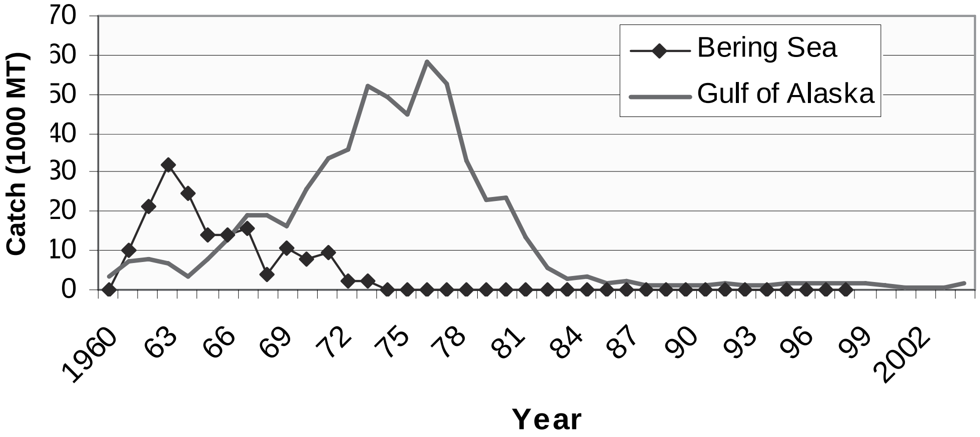

Fig. 120 Catch trend of Alaska shrimp fisheries from 1960 to 2003.

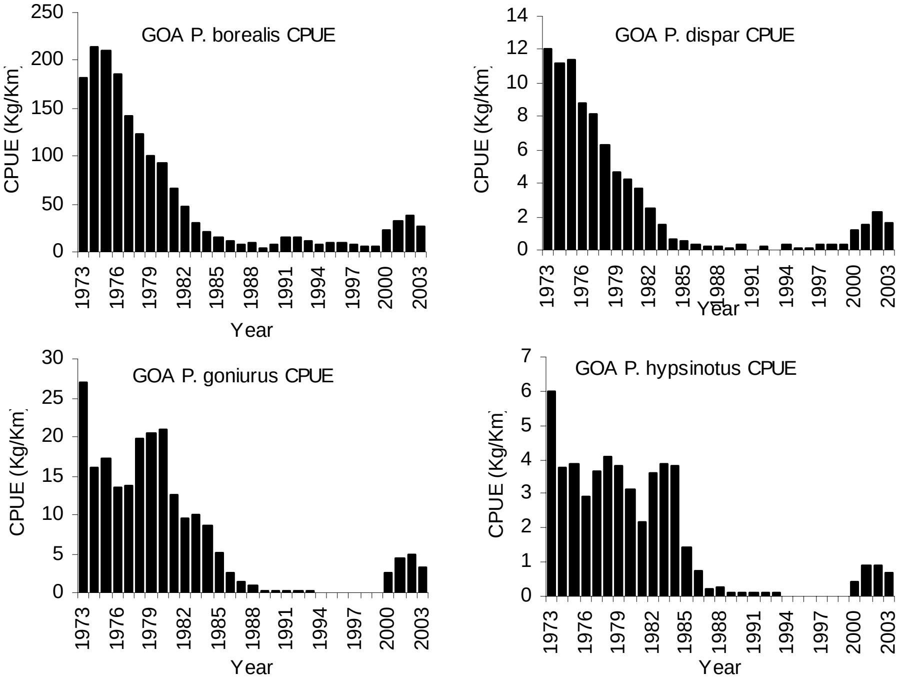

Fig. 121 Three-year average catch per unit effort (CPUE) (kg per km trawled) of all *Pandalus borealis*, *P. goniurus*, *Pandalopsis dispar*, and *Pandalus hypsinotus* in the Gulf of Alaska (GOA) small mesh survey from 1973 to 2003 (NPFMC, 2004, Appendix D).

Discussion

The warming of the Earth's atmosphere since the 1970s is expected to change the global environment in the immediate future. The Earth's air temperature had essentially been fairly stable from 200 AD until the 1970s. The average rise over the past 142 years has been only 1°C, but most of it has occurred since the 1970s. The oceans are gradually warming as well. While the change has been smaller (by 0.06°C on average; by 0.31°C for the top 300 m, and by 0.06°C for depths to 3,000 m; Levitus *et al.*, 2000), the effects of ocean warming are expected to be gradual and cumulative as the water mass of the oceans serve to hold heat for a long time. For the northern latitudes towards and into the Arctic Ocean, changes in the ocean environment are of great concern. Average temperatures in the Arctic region are rising twice as fast as they are elsewhere in the world. Arctic ice is getting thinner, melting and rupturing. If this trend continues, summers in the Arctic could become ice-free by the end of the century (ACIA, 2004).

A warmer Arctic will affect weather patterns all over the world. The ocean and atmosphere interact together in complex ways to produce what we know as climate. As water and air temperatures rise and atmospheric forces change, winds and ocean currents will change. There are predictions of the slowing of the major ocean currents in the Atlantic and the Pacific oceans as we know them now. But, how these long-term changes will come about, and how they would be modified from shorter term climatic events, are less predictable. In the case of the climatic forces off Alaska, this report has noted short-term dynamics of the ALPI and the intermediate-term change of the PDO index. These are just two of the many physical atmospheric parameters one can measure. Coupled to these atmospheric changes will be a complex set of inter-related changes to the ocean–air coupling system.

As ocean environments change in the North Pacific Ocean, ecological processes are expected to change, thus affecting all LMRs. While some of the features of these changes can be determined, for the most part, they are still unpredictable. This is particularly true when relating climate to ecosystem structure, since physical–biological coupling is non linear, and the biological response is an integration process of many physical signals from a number of time and space scales and sources. In addition, the impacts of higher temperatures on LMRs would get "integrated" into the impacts of other environmental changes and events that take place in the oceans simultaneously. The effects of climate change are expected to vary from species to species, and within different ecosystem settings. While changes are likely to occur for all the species, the cases discussed in this report are only some examples of how little we know of impending events.

Many hypotheses about oceanic food webs have been proposed to explain marine ecosystem regulation and population variations. The common hypotheses invoke bottom-up (Beamish and Bouillon, 1993) and top-down controls (Springer *et al.*, 2003; Worm and Myers, 2003) or combinations of both (Hunt *et al.*, 2002). Changes in nutrients affecting the productivity of the lowest trophic levels (*e.g.*, primary producers), which affect population abundance at the next higher trophic level (*e.g.*, herbivores) and associated trends of populations at other trophic levels in an ecosystem, are considered bottom-up control. Top-down control often functions through predation, initiated by animal predators, fishing or hunting, and may result in trophic cascades with opposite trends in population abundances between two trophic levels.

Environmental factors like temperature, wind, barometric pressure, or overall environmental conditions may affect food availability and larvae transport, growth and survival (*e.g.*, Koslow, 1984; Shepherd *et al.*, 1984; Koslow *et al.*, 1987; Hollowed and Wooster, 1992, 1995; Hare and Mantua, 2000), thus affecting recruitment strength of all LMRs. Of all the examples given in our review, no single factor or even a suite of factors can confidently be stated to be able to consistently explain variations in survival and abundance of the different resource components of the ecosystems. This observation is evidently made from the Zheng and Kruse (2006) studies on eastern Bering Sea crabs, where six different crab stocks in the same general shelf vicinity exhibited different patterns of recruitment. This observation emphasizes the difficulty of predicting how ocean warming would impact different components of the marine ecosystem.

Only the broadest of observations can be made as to which ocean conditions seem to favor the different components of living marine resources in the marine ecosystem. We have observed periods of high and low abundances of different species of seabirds, marine mammals, shrimps, crabs, groundfish, salmon, herring, and other species. We can generalize that shrimp, king crab, Tanner crab, and Steller sea lions were significantly more abundant before the 1970s when groundfish resources began to flourish. However, we cannot confidently relate how these abundances have changed with atmospheric and ocean conditions. Fishing and environment both play a role in influencing survival of living marine resources, but quantifying and separating the effects are difficult.

The ecosystem is a tightly linked biological and physical web. It is not easy to dissect and understand the coupling of the web. Our discussion merely has pointed out some major signals in the components of Alaska's marine ecosystems and attempts to identify potential changes to these components as ocean conditions continue to warm. The trend of research and management of the fisheries resources is towards an ecosystem perspective. We merely focus on the principal signals of the dynamics of the principal component species. Even with this simplified perspective, it is still difficult to understand and predict what would happen as the oceans around Alaska warm up and are affected by shorter term atmospheric forcing. With the movement towards the evaluation of climatic change on the whole ecosystem, it is anticipated that adding a higher degree of complexity to the research can only help to explain what may be difficult to predict now. A research program known as Loss of Sea Ice (LOSI) is being implemented by NOAA to research the issues.

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Appendix 1

Terms of Reference

1. Identify key examples of species that have been affected by climate and ocean changes;
2. Investigate and assess the impact of inter-annual and decadal-scale physical changes in relation to fishing effects;
3. Describe or hypothesize the mechanisms linking climate and ocean changes to changes in the population dynamics;
4. Using these mechanism and indices of climate change, examine the possibility of long-term forecasting of changes in population dynamics and ecosystem structure.

Appendix 2

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Appendix 3

Species List

A

Albacore tuna (*Thunnus alalunga*)
Amphipoda (*i.e.*, *Themisto gracilipes*, *Themisto japonica*, *Primno abissalis*)
Anchovy (*Engraulis japonicus*) also known as Japanese anchovy
Arrow worm (*Sagitta crassa*)
Arrowtooth flounder (*Atheresthes stomias*)
Atlantic cod (*Gadus morhua*)
Atlantic salmon (*Salmo salar*)
Atka mackerel (*Pleurogrammus monopterygius*)
Aurora rockfish (*Sebastes aurora*)

B

Big-eye sardine (*Etrumeus teres*)
Bighead croaker (*Collichthys niveatus*)
Big skate (*Raja binoculata*)
Black rockfish (*Sebastes melanops*)
Blue crab (*Portunus trituberculatus*)
Blue king crab (*Paralithodes platypus*)
Bocaccio rockfish (*Sebastes paucispinis*)
Butter sole (*Isopsetta isolepis*)

C

Canary rockfish (*Sebastes pinniger*)
Capelin (*Mallotus villosus*)
Chaetognatha (*i.e.*, *Sagitta crassa*) also known as arrow worms
Cherry salmon (*Oncorhynchus masou*)
Chilipepper rockfish (*Sebastes goodei*)
China rockfish (*Sebastes nebulosus*)
Chinook salmon (*Oncorhynchus tshawytscha*)
Chub mackerel (*Scomber japonicus*) also known as common mackerel
Chum salmon (*Oncorhynchus keta*)
Coho salmon (*Oncorhynchus kitusch*) also known as silver salmon
Common squid (*Todarodes pacificus*) also known as Japanese flying squid
Copepoda (*i.e.*, *Calanus pacificus, Neocalanus, paracalanus, Pseudocalanus*)
Copper rockfish (*Sebastes caurinus*)
Curlfin sole (*Pleuronichthys decurrens*)
Cuttlefish (*Sepiella maindroni*)

D

Darkblotched rockfish (*Sebastes crameri*)
Dover sole (*Microstomus pacificus*)
Dusky rockfish (*Sebastes ciliatus*)

E

English sole (*Parophrys vetulus*)
Eelgrass (*Zostera*)
Euphausiida (*i.e.*, *Euphausia pacifica* or *Thysanoessa longipes*), also known as krill

F

Filefish (*Thammaconus modestus*)
Flathead sole (*Hippoglossoides elassodon*)

G

Gizzard shad (*Clupanodon punctatus*)
Golden / brown king crab (*Lithodes aequispina*)
Greenland turbot (*Reinhardtius hippoglossoides*)
Greenstriped rockfish (*Sebastes elongatus*)

H

Hairtail (*Trichiurus lepturus*) also known as largehead hairtail (may be also *T. haumela*)
Half-fin anchovy (*Setipinna taty*) also known as scad
Harlequin rockfish (*Sebastes variegatus*)
Hydroid (hydrant) (*Obelia*)

J

Jack mackerel (*Trachurus japonicus*) also Japanese jack mackerel or horse mackerel
Japanese sardine (*Sardinops melanostictus*) also known as Japanese pilchard
Japanese sardinella (*Sardinella zunasi*) also known as large-eyed herring

K

Kelp greenling (*Hexagrammos decagrammus*)

L

Lingcod (*Ophiodon elongatus*)
Longnose skate (*Raja rhina*)
Longspine thornyhead (*Sebastolobus altivelis*)

M

Mantis shrimp (*Oratosquilla oratoria*)

N

Neon flying squid (*Ommastrephes bartrami*)
Northern shrimp (*Pandalus borealis*) known as a deep-water shrimp in Alaska
Northern rockfish (*Sebastes polyspinis*)
Northern rock sole (*Lepidopsetta polyxystra*)

P

Pacific cod (*Gadus macrocephalus*)
Pacific hake (*Merluccius productus*) also known as North Pacific hake
Pacific halibut (*Hippoglossus stenolepis*)
Pacific herring (*Clupea pallasii*)
Pacific ocean perch (*Sebastes alutus*)
Pacific sardine (*Sardinops sagax*)
Pacific saury (*Cololabis saira*)
Penaeid shrimp (*Penaeus chinesis*)
Petrale sole (*Eopsetta jordani*)
Pink salmon (*Oncorhynchus gorbuscha*)
Pomfret (*Stromateoides argenteus*)

Q

Quillback rockfish (*Sebastes maliger*)

R

Redbanded rockfish (*Sebastes babcocki*)
Red king crab (*Paralithodes camtschatica* or *camtschaticus*)
Rednose anchovy (*Thrissa kammalensis*)
Redstripe rockfish (*Sebastes proriger*)
Rex sole (*Glyptocephalus zachirus*)
Rock sole (*Lepidopsetta bilineata*)
Rosethorn rockfish (*Sebastes helvomaculatus*)
Rougheye rockfish (*Sebastes aleutianus*)

S

Sablefish (*Anoplopoma fimbria*)
Sand sole (*Psettichthys melanosticus*)
Sandpaper skate (*Bathyraja interrupta*)
Scad (*Decapterus maruadsi*), also known as round scad
Scaled sardine (*Harengula zunasi*)
Seabass (*Lateolabrax japonicus*)
Shrimp (*Pandalus* and *Pandalopsis* spp.)
  Pandalus goniurus known as a shallow-water shrimp in Alaska
  Pandalus dispar known as a deep-water shrimp in Alaska
  Pandalus hypsinotus known as a shallow-water shrimp in Alaska
Sharpchin rockfish (*Sebastes zacentrus*)
Shortbelly rockfish (*Sebastes jordani*)
Shortraker rockfish (*Sebastes borealis*)
Shortspine thornyhead (*Sebastolobus alascanus*)
Silvergray rockfish (*Sebastes brevispinis*)
Skate (*Roja porosa*)
Skipjack tuna (*Katsuwonus pelamis*)
Slender sole (*Lyopsetta exilis*)
Small yellow croaker (*Pseudosciaena polyactis*)
Snow crab (*Chionoecetes opilio*)
Sockeye salmon (*Oncorhynchus nerka*), also known as red salmon

Southern rough shrimp (*Trachypenaeus curvirostris*)
Spanish mackerel (*Scomberomorus niphonius*) also known as Japanese Spanish mackerel
Spiny dogfish (*Squalus acanthias*)
Splitnose rockfish (*Sebastes diploproa*)
Spotted ratfish (*Hydrolagus colliei*)
Squid (*Loligo beak*)
Starry flounder (*Platichthys stellatus*)
Steller sea lion (*Eumetopias jubatus*)

T

Tanner crab (*Chionoecetes bairdi*)
Thornyhead rockfish (*Sebastolobus* spp.) see longspine and shortspine thornyhead
Threadsail filefish (*Thamnaconus modestus*)
Tiger rockfish (*Sebastes nigrocinctus*)

V

Vermilion rockfish (*Sebastes miniatus*)
Viral hemorrhagic septicemia virus (VHSV), *i.e., Ichthyophonus hoferi*

W

Walleye pollock (*Theragra chalcogramma*), also known as Alaskan pollock
White croaker (*Argyrosomus argentatus*)
Widow rockfish (*Sebastes entomelas*)
Wolf eel (*Anarrhichthys ocellatus*)

Y

Yellow drum (*Nibea albiflora*)
Yelloweye rockfish (*Sebastes ruberrimus*)
Yellowfin sole (*Limanda aspera*)
Yellowmouth rockfish (*Sebastes reedi*)
Yellowtail rockfish (*Sebastes flavidus*)

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