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^{o}N latitude off Japan to 37^{o}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.