## 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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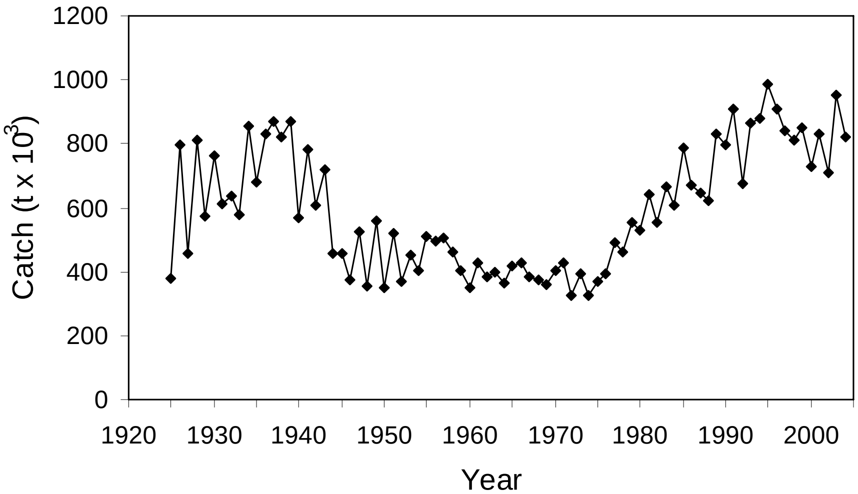


**Fig. 1** Total catch of Pacific salmon by Canada, Japan, Russia and the United States from 1925 to 2004.

## 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.

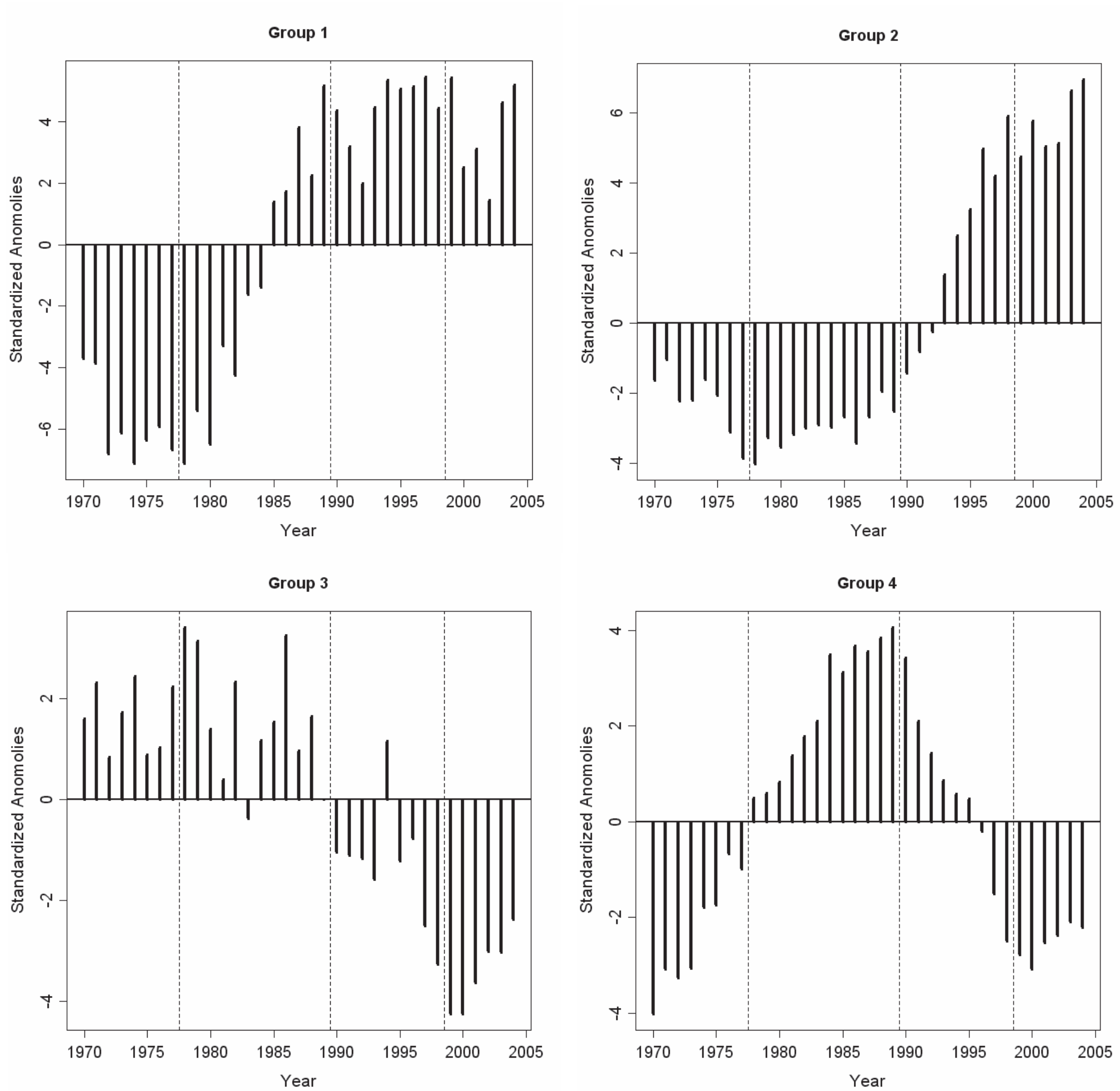


**Fig. 2** Summed standardized anomalies for species within the four groups identified in this study. The anomaly for each species was lagged by the number of years it would take for the species to be recruited into the fishery. The dashed vertical lines represent the timing of the major regime shifts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

**Table 2** Run tests for the four groups.

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

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.