Climate and Exceptional Fish Production off the West Coast of North America

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From 1976 to 1978 there was a change in the climate over the North Pacific Ocean. The Aleutian Low intensified and there was a warming of the sea surface adjacent to North America and a cooling offshore. Associated with this change was a period of exceptional fish production. Strong year classes and above-average survival occurred for many commercially important species all along the west coast of Canada and the United States. Trends in total salmon catches increased primarily from increased salmon production in Alaska. Some stocks of maturing pink (*Oncorhynchus gorbuscha*), coho (*O. kisutch*), and chinook salmon (*O. tshawytscha*) also had above-average growth in 1977. A majority of commercially important nonsalmon species that spawned from California to the Bering Sea and have a wide range of life history types also had exceptionally strong year classes from 1976 to 1978. The exceptional survival appears to be related to improved ocean productivity caused by changes in the intensity of the Aleutian Low.

De 1976 à 1978 a eu lieu une modification du climat au-dessus du Pacifique nord. La dépression des Aléoutiennes s'est intensifiée, et on a observé un réchauffement de la surface de la mer à proximité de l'Amérique du Nord, et un refroidissement au large. Ce changement s'est accompagné d'une période de production de poissons exceptionnelle. De fortes classes annuelles et un taux de survie au-dessus de la moyenne ont été notés pour de nombreuses espèces commercialement importantes tout le long de la côte ouest du Canada et des États-Unis. Les tendances des prises totales de saumon ont augmenté, ce qui est dû principalement à l'accroissement de la production salmonicole en Alaska. Certains stocks de saumon rose (*Oncorhynchus gorbuscha*), coho (*O. kisutch*) et quinnat (*O. tshawytscha*) ont aussi présenté en 1977 une croissance au-dessus de la moyenne. La majorité des espèces commercialement importantes de poissons autres que des salmonidés, qui fraient de la Californie à la mer de Béring et ont des cycles biologiques très divers, ont aussi connu des classes annuelles exceptionnellement fortes de 1976 à 1978. Ce taux de survie exceptionnel semble être lié à une amélioration de la productivité marine causée par la modification de l'intensité de la dépression des Aléoutiennes.

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Understanding recruitment is fundamental to understanding how to sustain fisheries. Environmental influences on recruitment receive less attention in traditional population dynamics because the biological processes regulating recruitment are generally poorly understood. Neglecting or averaging environmental effects on stock size oversimplifies the population dynamics process and will ultimately lead to management problems. Identifying close relationships between recruitment strength (year-class strength) and environmental conditions probably will help clarify the population dynamics process and may even improve the accuracy of models that forecast long-term abundance trends.

In this report, I identify a period from 1976 to 1978 when major changes in fish abundance occurred and then relate the abundance changes to changing environmental conditions. I examined catch trends of many of the important west coast marine fishes in the commercial catches of Canada and the United States. Some data series appear short or incomplete because they do not begin until the early 1970s or because they end in the early 1980s, as long-lived species such as Pacific halibut (*Hippoglossus stenolepis*) or Pacific ocean perch (*Sebastes alutus*) are not recruited to the commercial fishery until they are 8-12 yr old. Thus, information on the year-class strength of some commercially important species is available only from the early 1970s to the early 1980s.

Brief descriptions of the climate and the oceanography of the North Pacific Ocean and the Strait of Georgia are included to provide background information for the discussion of environmental changes that occurred in 1976 and 1977. Descriptions and discussions of climate and oceanography are for the winter period because most demersal fishes off the west coast of North America spawn in the winter (Hart 1973) and it is known that there is a relationship between salmon production and the winter climate over the northern North Pacific Ocean (Beamish and Bouillon 1993).

Climate and Oceanography in the North Pacific

During the winter, the climate over the North Pacific Ocean is dominated by the Aleutian Low (Fig. 1), a deep extensive low pressure area that develops late in the year (Trenberth 1990; Beamish and Bouillon 1993). The low begins to break down in the spring and is replaced in the summer by an area of extensive high pressure. The major ocean currents are generated by the

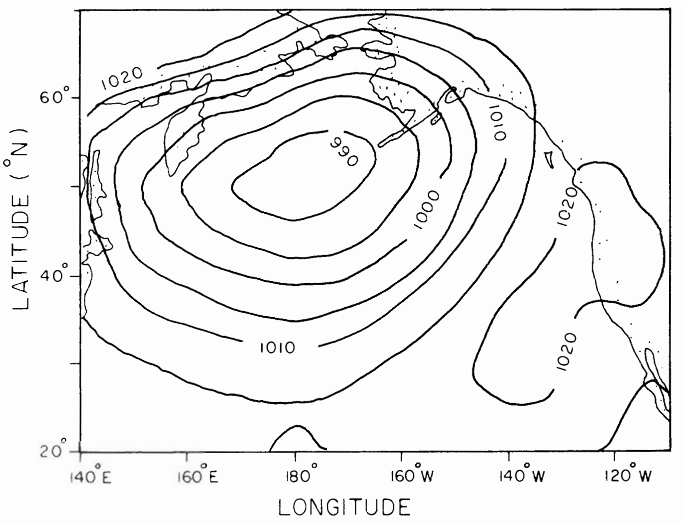

FIG. 1. Aleutian Low that formed from December 1976 to February 1977. Area less than 1000 kPa indicates the extent of this extreme low (from Hamilton 1984). The contour interval is 5 kPa.

resulting surface winds, with the strength of the currents related to the strength of the winds. Seasonal differences in the direction of the winds determine if surface currents (called Ekman transport) flow inshore or offshore (Dodimead 1984; Freeland et al. 1984).

In the North Pacific, the ocean circulation consists of a clockwise-flowing Central Pacific gyre and a counter-clockwise-flowing Alaskan gyre. The boundary between these two currents, the Subarctic Current, divides into two branches as it nears the coast of North America at about latitude 45–50°N. One branch, the California Current, flows south and the other, the Alaska Current, flows north off the coasts of British Columbia and Alaska. As the Aleutian Low develops in the fall, the circulation around the Alaska gyre intensifies (Thomson 1981). During periods of strong Aleutian Lows, there is strong onshore transport of surface currents (the Ekman layer) and intense downwelling along the coast as far south as central California. This mass of water flowing towards the coast must be replaced by water from below. Hence, there is a shallowing of the upper mixed layer to the north in the central Pacific Ocean (Thomson 1981) bringing cooler, nutrient-rich water to the surface.

Climate and Oceanographic Changes in the Late 1970s

The Aleutian Low of 1976–77 (Fig. 1) was the most intense low since 1940–41 (Beamish and Bouillon 1993). From December 1976 through May 1977, most of the northern North Pacific Ocean was dominated by this area of intense low pressure. This intense low also signaled a change in the pattern of winter (November–March) low pressures (Trenberth 1990). Trenberth (1990) showed that from 1956 until 1976, the mean sea level pressure over the North Pacific Ocean was approximately 1012.8 mbars (1 mbar = 100 Pa). After 1976, (1977–88) it was approximately 1010.8 mbars, a drop of 2 mbars over the vast area of the North Pacific Ocean (Fig. 2). The centre of the Aleutian Low moved farther east and became deeper by an average of 4.3 mbars for the five winter months and deeper by 7–9 mbars in January.

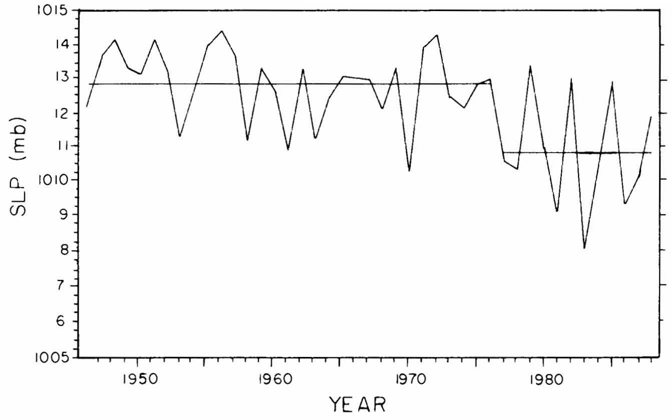

FIG. 2. Mean sea level pressure in the North Pacific Ocean from November to March showing the change in the pattern of the winter climate that occurred in 1976 (from Trenberth 1990).

Another indication of a climate change over the North Pacific in the late 1970s is the change that occurred in sea surface temperatures. Sea surface temperatures in the Northeast Pacific Ocean have two general patterns: one, where sea surface temperatures along the coast of North America are below normal when temperatures farther offshore are above normal and a second type that is the opposite (McLain 1984). These patterns are most obvious in the winter. The pattern oscillated over the years 1957–76 (Fig. 3). In the summer of 1976, however, it changed from having below-normal sea surface temperatures adjacent to shore to having above-normal sea surface temperatures close to shore (McLain 1984). The increase in sea surface temperatures lasted until at least the mid-1980s and was most dramatic in the Northeast Pacific Ocean (Chelton 1984; Fig. 4). A time series of sea surface temperatures using a running average of three months shows that a period of lower than usual sea surface temperatures came to an end in 1976 (Fig. 4).

The abrupt change in climate in 1976 was clearly shown by Ebbesmeyer et al. (1991) using combined records of 40 environmental variables that reflected environmental conditions for 1968–84 off the west coast of North America in the vicinity of Puget Sound. The changes were identified in the Gulf of Alaska (Royer 1989) and off California (Bakun 1990). The climate shift started a new climate regime over a vast area of the Pacific Ocean and North America (Kerr 1992). In general, the period 1977–86 featured very large air temperature anomalies in the North Pacific basin. There was a general warming exceeding 1.5°C over Alaska (Fig. 5) and a cooling of less than 0.75°C in the central and western North Pacific (Trenberth 1990). This pattern of warming over Alaska and cooling in the central and western North Pacific would be expected with more intense Aleutian Lows because warmer, moister air would be carried along the west coast of North America into Alaska. At the same time, cooler, southward flowing air would be found in the central and western North Pacific.

In British Columbia, the winter of 1975–76 was one of the warmest and wettest on record. Records from a number of locations throughout British Columbia indicate total precipitation in the winter of 1975-76 as the highest on record over the period 1939-89 (Fig. 6A). There was also a change in the long-term precipitation pattern. Beginning in the mid-1970s, average annual precipitation, measured from June in one year to May in the next, increased near the coast (Fig. 6B), and since 1980,

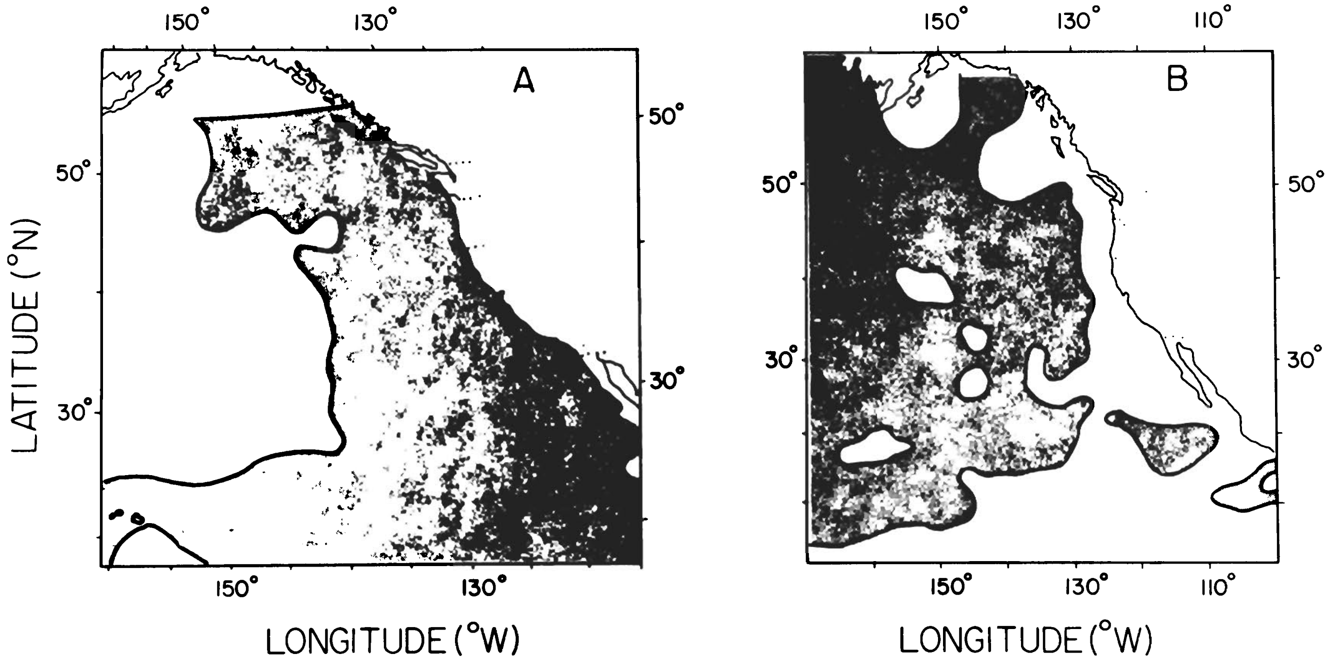

FIG. 3. Pattern of sea surface temperature anomaly (°C) for (A) January 1972 showing below-normal temperatures (shaded area) close to shore and (B) January 1983 showing above-average temperatures close to shore (unshaded area) (from McLain 1984).

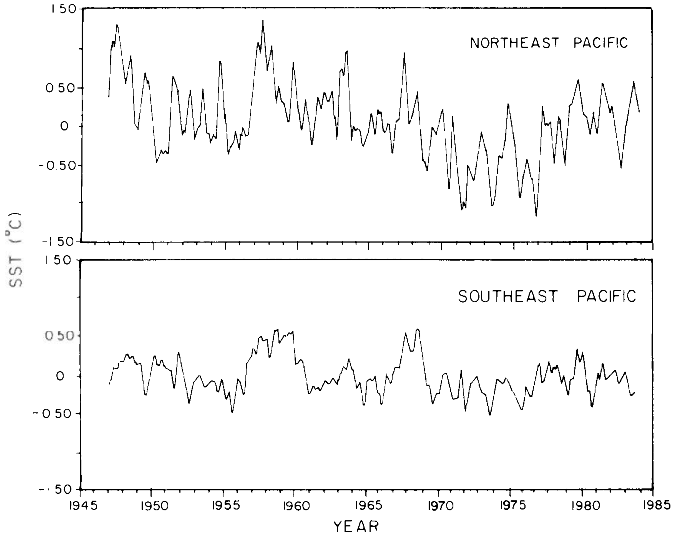

FIG. 4. Time series of sea surface temperature in the eastern Pacific Ocean presented as a 3-mo running average showing the trend to increasing temperatures between 1972 and 1979 in the Northeast and Southeast quadrants of the North Pacific Ocean (from Chelton 1984).

precipitation has been above the long-term average each year. In contrast, discharge from the Fraser River, the largest and most important river in British Columbia, was the highest on record in 1976 (Fig. 7) but declined after that year. This decline in discharge appears to be related to a decline in snowpack in the interior of British Columbia that appears to have started in 1977. The annual average snowpack from 24 stations within the Fraser River Basin from 1977 to 1988 was 22% less than the annual average snowpack from 1960 to 1976 (D. Moore, Department of Geography, Simon Fraser University, Burnaby, B.C.). It appears, therefore, that precipitation along the coast increased, but decreased inland. Because most water in the Fraser River comes from the interior of British Columbia, the annual discharge declined.

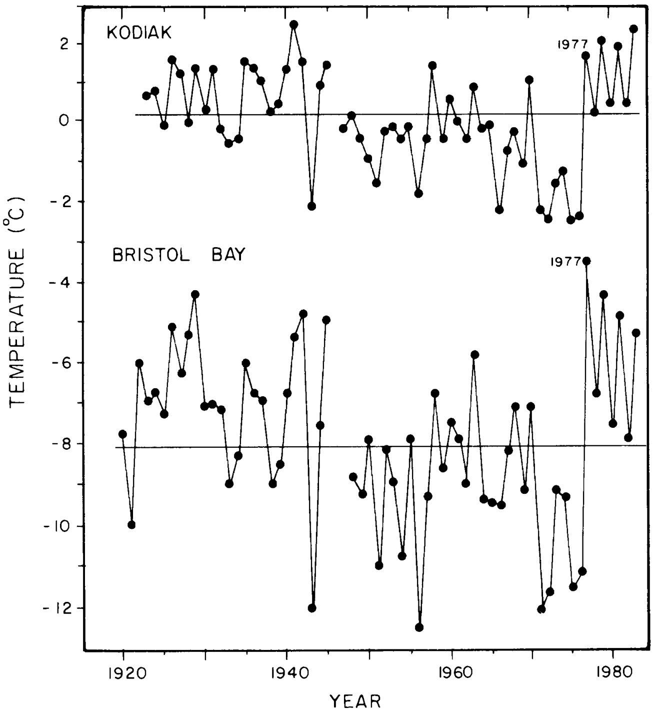

FIG. 5. Average winter (November–March) air temperature for Kodiak and Bristol Bay, Alaska, showing abrupt increases in 1977 (from Rogers 1984).

The Strait of Georgia is the most important marine area off the west coast of Canada and one of the most important salmon-producing areas in the North Pacific Ocean. The physical oceanography is mainly affected by runoff and nutrient-rich inflowing deep water of oceanic origin (Tully and Dodimead 1957). The major source of runoff is the Fraser River, contributing almost 80% of the runoff (Waldichuk 1957).

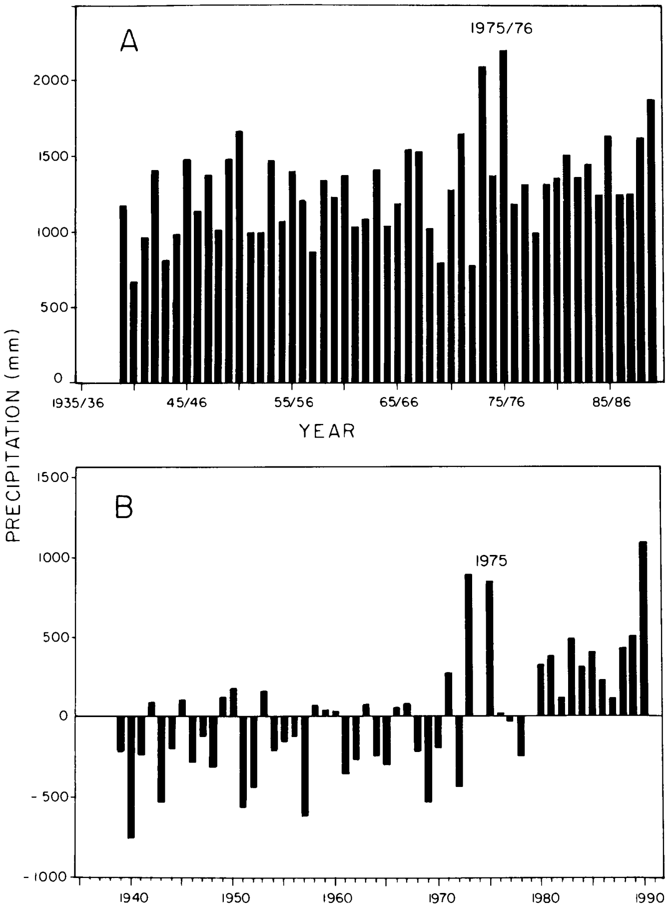

FIG. 6. (A) Total precipitation (rain and snow) for October–March and (B) precipitation anomaly for June–May at Hope, B.C. (data from the Temperature and Precipitation Abstracts, Atmospheric Environment Service, Canada).

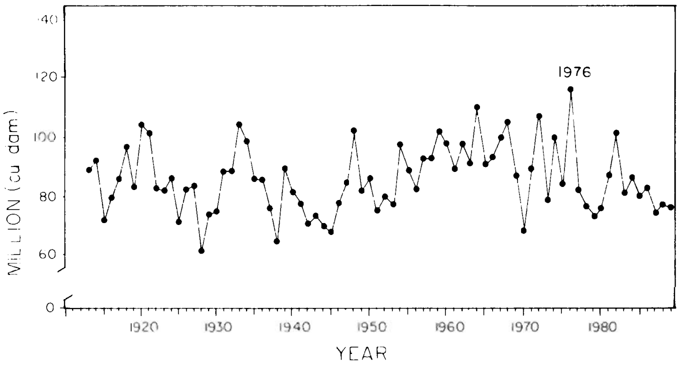

FIG. 7. Total annual discharge from the Fraser River (Environment Canada 1990).

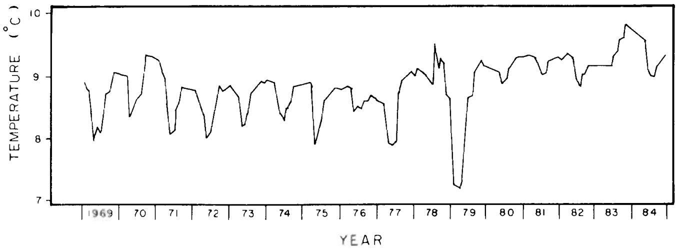

FIG. 8. Bottom water temperatures in the Strait of Georgia (data courtesy of R.E. Thomson, Institute of Ocean Sciences, Sidney, B.C.). Data from 1985 to the present were not available.

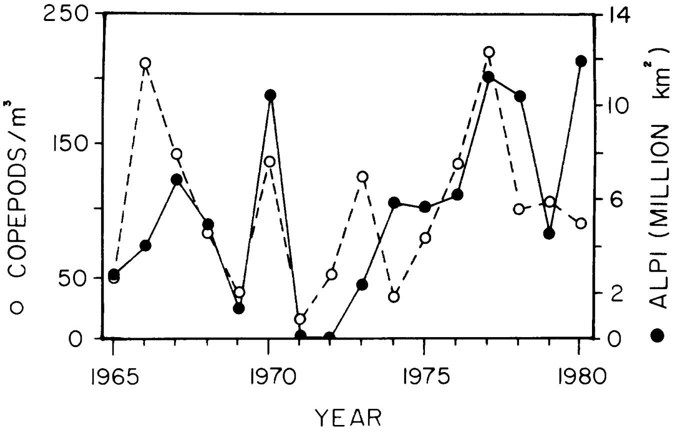

FIG. 9. Relationship ($r = 0.50$, $p < 0.05$) between copepod abundance at Ocean Station "P" (broken line, open circles) (from Fulton 1983) and the Aleutian Low Pressure Index (ALPI) (solid line, solid circles) (from Beamish and Bouillon 1993).

Bottom water temperatures have been recorded in the Strait of Georgia by the Department of National Defence since 1969. The annual cycle of temperature change reflects the change in the volume of cool oceanic water that enters the Strait of Georgia to replace surface water transported out as a consequence of Fraser River discharge. The annual temperature cycle of the bottom water was relatively uniform until 1976 (Fig. 8), but from 1976 until 1980 the cycle was disrupted. After 1980, a new cycle was established; average annual bottom water temperatures were warmer and there was less annual fluctuation. The timing of the change in this annual pattern of bottom water temperature coincides with the other changes in climate and oceanography, including the record discharge from the Fraser River.

The longest continuous time series of plankton abundance changes in the central North Pacific Ocean, collected at Ocean Station "P" (Fulton 1983), was discontinued in 1980. The maximum average abundance of copepods, for the period most larval fish would be feeding on copepods (March–May), occurred in 1977 (Fig. 9). There was a significant relationship between the intensity of the Aleutian Low and copepod production at Ocean Station "P" (McFarlane and Beamish 1992; Beamish and Bouillon 1993; Fig. 9). The average annual production of copepods increased 1.5 times from 1976 to 1980 compared with the average from 1965 to 1975. Estimates of zooplankton biomass in the central subarctic Pacific Ocean doubled from the 1956 to 1962 period to the 1980 to 1989 period (Brodeur and Ware 1992), indicating that the increase in copepod abundance that occurred in the late 1970s at Ocean Station "P" probably persisted into the 1980s. Because copepods are the dominant species in the zooplankton (McFarlane and Beamish 1992) and a principal food for many marine species, there is a clear link between the intensification of the Aleutian Low and fish production.

It is clear that the climate change that began in 1976 was a major event all along the west coast of North America that was associated with increases in primary and secondary production on a large scale. Associated with these changes were major changes in fish abundance.

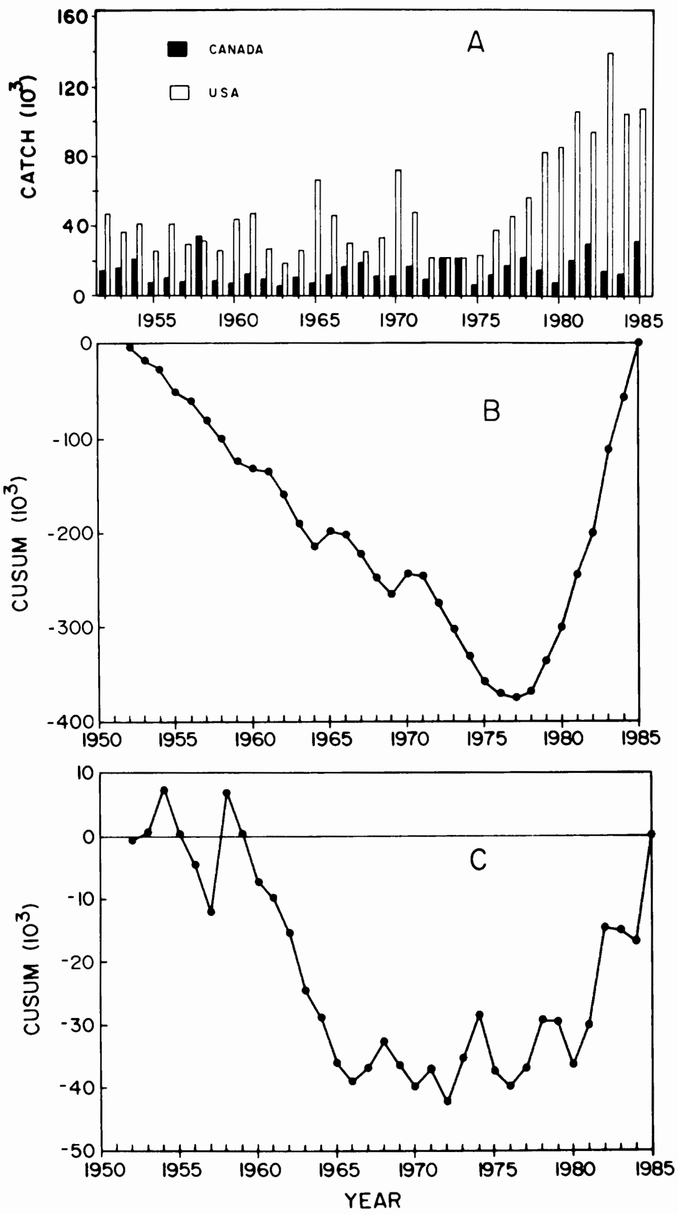

FIG. 10. (A) Sockeye salmon catch (t) by country, (B) cumulative sum of sockeye salmon catch (t) by the United States, 1952–85, showing the change in trend beginning in 1977, and (C) cumulative sum of sockeye salmon catch (t) by Canada, 1952–85 (INPFC 1979, 1977–89).

Changes in Salmon Abundance

Pacific salmon constitute a group of important species in the commercial fishery off the west coast of Canada and the United States and as a group are documented by one of the longest and most reliable data bases. Trends in all-nation catches of pink (*Oncorhynchus gorbuscha*), chum (*O. keta*), and sockeye salmon (*O. nerka*) changed in the late 1970s from about 1977 to 1979 (Beamish and Bouillon 1993). Average catches in the time series from 1925 to 1988 went from historic lows in the early 1970s to levels in the late 1980s that were close to the historic highs. In this report, I looked for stock-specific evidence of the timing and magnitude of this change in important North American commercial salmon fisheries. I reviewed the evidence that indicated that trends in the catches of salmon changed in the late 1970s and I also included biological and related information to show that changes in size and behaviour were associated with the trend of increasing salmon production.

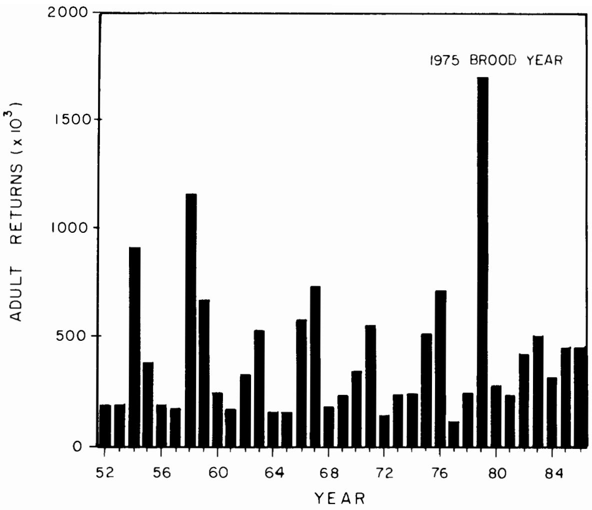

FIG. 11. Total return of adult sockeye salmon to the Stellako River (catch + spawning adults) (from Cass 1989). This stock is one of the Fraser River stocks that had exceptional adult returns in 1979.

Sockeye Salmon (*Oncorhynchus nerka*)

Trends in catches can be demonstrated using cumulative sum charts (CuSum) charts (Murdoch 1979). CuSum plots use information contained in a time series to identify when changes in catch occurred. The slope of the graph is a measure of the mean trend, and a change in the slope indicates a change in the trend.

Ages are assigned to salmon to indicate the year of spawning. These ages are not equivalent to ages assigned to most other fishes and are not directly comparable with ages of nonsalmon species in this article. In most cases, sockeye salmon that entered the sea in 1977 were the 1975 brood year or fish that spawned in 1975. Once in salt water, most sockeye salmon spend 2 yr (winters) at sea before returning to spawn. Therefore, fish returning from the 1975 brood year in 1979 year are considered to be age 4.

Most of the increase in total North American salmon catch in the mid-1980s resulted from increased sockeye salmon catches in Alaska (Fig. 10A). The change in catch trends in Alaska occurred about 1977 (Fig. 10B). The trend in Canadian catches was more variable, changing approximately in 1959, 1966, and 1980 (Fig. 10C), with the increase in the mean catch beginning in the early 1980s.

In British Columbia, there are two major areas that produce sockeye salmon: the Skeena River drainage and the Fraser River drainage. A major difference between the Skeena River stocks and the Fraser River stocks is the presence of strong cycles of abundance in the Fraser River (Vernon 1982). The reason for the cycles is unknown, but their existence requires that survival comparisons be made for individual stocks or cycle years. Most sockeye salmon from the Fraser River that went to sea in 1977 (1975 brood year) were produced from some of the smaller stocks or from the less productive years of the larger stocks. Using the catch estimates compiled by Cass (1989), strong year classes (brood years) were produced for about one half of these stocks (Fig. 11). The average number of adults that return for each female spawner for all Fraser River stocks is 4.88 (Cass 1989). The return per spawner for the 1975 brood year or all the sockeye from the Fraser River that went to sea in 1977 was 6.73,

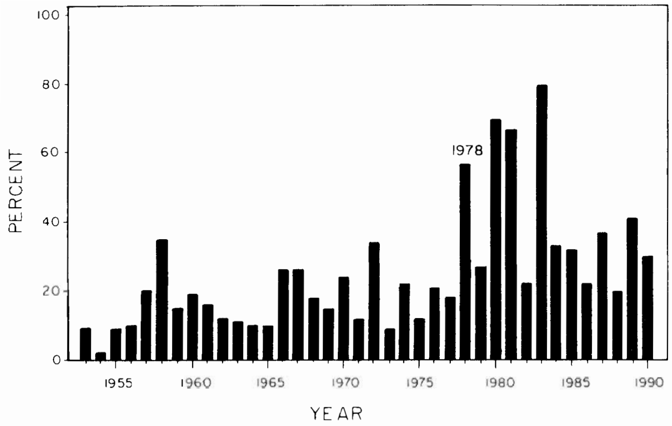

FIG. 12. Percent of Fraser River sockeye salmon returning to the Fraser River through Johnstone Strait (data courtesy of the Pacific Salmon Commission, Vancouver, B.C.). A high proportion returned through Johnstone Strait in 1978, 1980, 1981, and 1983.

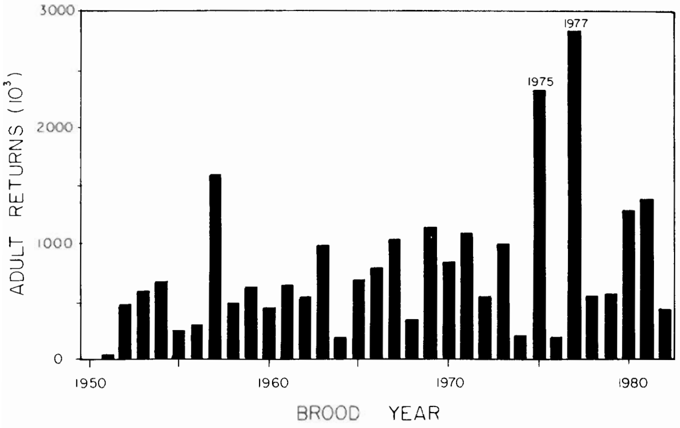

FIG. 13. Estimated number of age 4 sockeye salmon (catch + escapement) returning to the Skeena River (data courtesy of M. Henderson and R. Diewert. Department of Fisheries and Oceans, Vancouver, B.C.).

the highest survival rate for this cycle since the 1955 spawning. The egg to smolt survival for the Chilko River stock in the Fraser River was almost average for the 1975 brood year (Cass 1989). However, the smolt to adult survival was above the long-term average, indicating that for this stock the improved survival probably occurred in the sea.

The behaviour of sockeye salmon returning to the Fraser River changed in 1978. Sockeye salmon can return through Juan de Fuca Strait or through Johnstone Strait and through the Strait of Georgia. The percentage returning through Johnstone Strait has been estimated since 1953 (Fig. 12). In 1978, the percentage increased, and it increased further in 1980, 1981, and 1983.

In the Skeena River, sockeye salmon going to sea in 1977 and 1979 had above-average survival. The returns from fish that entered the ocean in 1977 (the 1975 brood year) were the highest since 1950 (Fig. 13). The returns from fish that went to sea in 1979 (1977 brood year) also were exceptionally high (Fig. 13).

Sockeye salmon in Alaska live in fresh water for 2 or 3 yr and return to fresh water after 2 or 3 yr in salt water. Adults, therefore, can be 4, 5, or 6 yr old, but most adults are 5 yr and most of these remained in fresh water for 2 yr. The returns from sockeye that

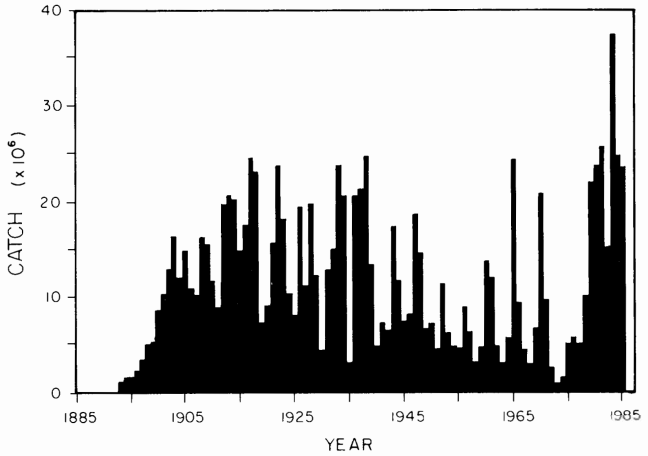

FIG. 14. Commercial catch of sockeye salmon in Bristol Bay, Alaska, showing an abrupt increase in catch beginning in the late 1970s (from Minard and Meacham 1987).

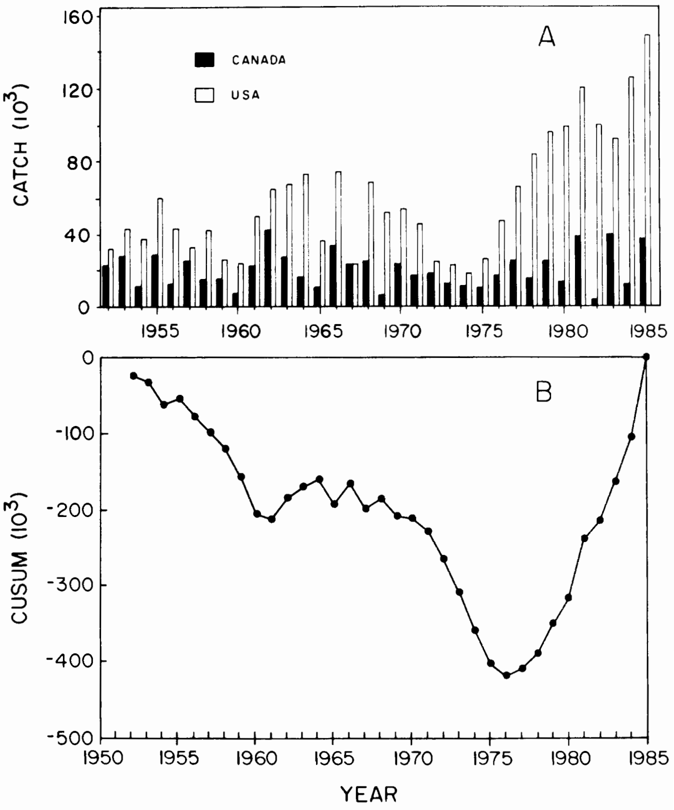

FIG. 15. (A) Pink salmon catch (t) by country (INPFC 1979, 1977–89) and (B) cumulative sum of the pink salmon catch (t) by Canada and the United States, 1952–85, showing the increasing abundance trend that started in 1977.

went to sea in 1977 produced record high catches (Minard and Meacham 1987; Fig. 14), particularly in the Kvichak River, the largest producer of sockeye salmon in the catch. There is a 5-yr cycle in the Kvichak River that produced strong year classes in 1975 and 1980. Thus, fish from the 1975 brood year that went to sea in 1977 and 1978 would be expected to produce another strong cycle year. However, fish from the much weaker 1974 brood year that remained in fresh water for 3 yr and went to sea in 1977 had the highest return per spawner on record (estimated

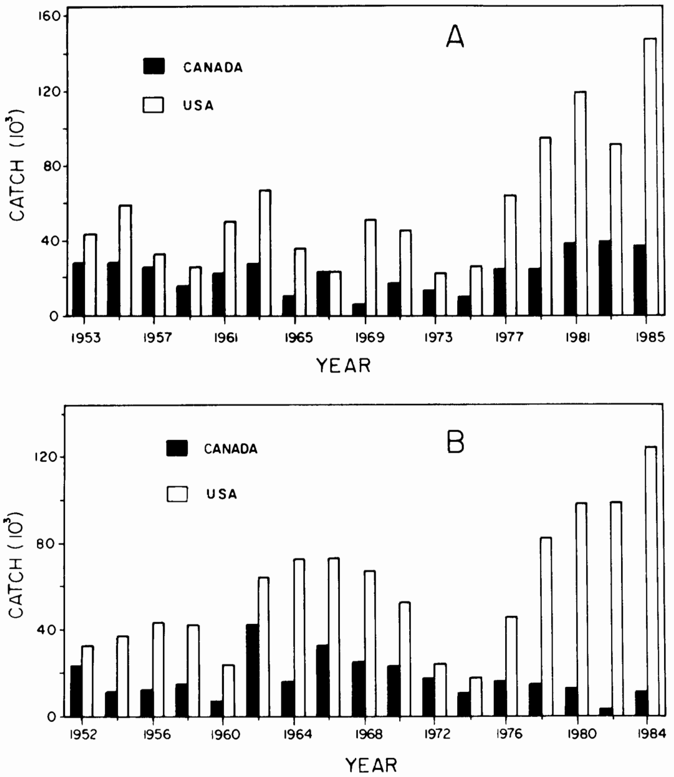

FIG. 16. (A) Odd-year and (B) even-year pink salmon catch (t) by country (INPFC 1979, 1977–89).

from table 1 in Eggers and Rogers 1987). Sockeye salmon production in Alaska continued to increase into the 1980s resulting in exceptional catches.

Pink Salmon (*Oncorhynchus gorbuscha*)

Pink salmon are the most abundant salmon in British Columbia and in the North Pacific Ocean. Eggs hatch in the spring following spawning and fry migrate almost immediately to sea. Pink salmon remain at sea for almost 18 mo when they return to their river of origin to spawn. Odd- and even-year spawning populations spawn in odd and even calendar years. In the south, pink salmon tend to spawn in odd-numbered years and in the north they tend to spawn in even-numbered years. In some rivers, such as the Fraser River, most spawners are almost exclusively of one type. Returns to the Fraser River in even years such as 1976 or 1978 are negligible. In the Skeena River the runs occur in both years, with the odd-year runs being slightly larger than the even-year runs. Because the runs remain genetically isolated, pink salmon catch trends need to be assessed by odd- and even-year spawning populations as well as total catch.

North American pink salmon catches increased in the late 1970s (Fig. 15A). Trends in catch (Fig. 15B) changed in 1977, approximately at the same time as those of sockeye salmon. The total catch increased from an average of 45.2×10^3 t in the period 1971–76 to an average of 126.4×10^3 t from 1977 to 1985. This catch pattern was strongly influenced by the United States catch that came mostly from Alaska. In the United States, the trend in Alaskan catches was most obvious in 1978 and 1979, the 1976 and 1977 brood years that went to sea in 1977 and 1978. In the United States, both odd- and even-year runs increased whereas in Canada, only the odd-year populations increased (Fig. 16). An increase in Canadian catches was apparent in 1977 and 1979, but most obvious in 1981, the 1979 brood year. The Canadian catch pattern was much more variable but shows a decline in the late 1960s and early 1970s similar to the United States and a recovery beginning in 1979.

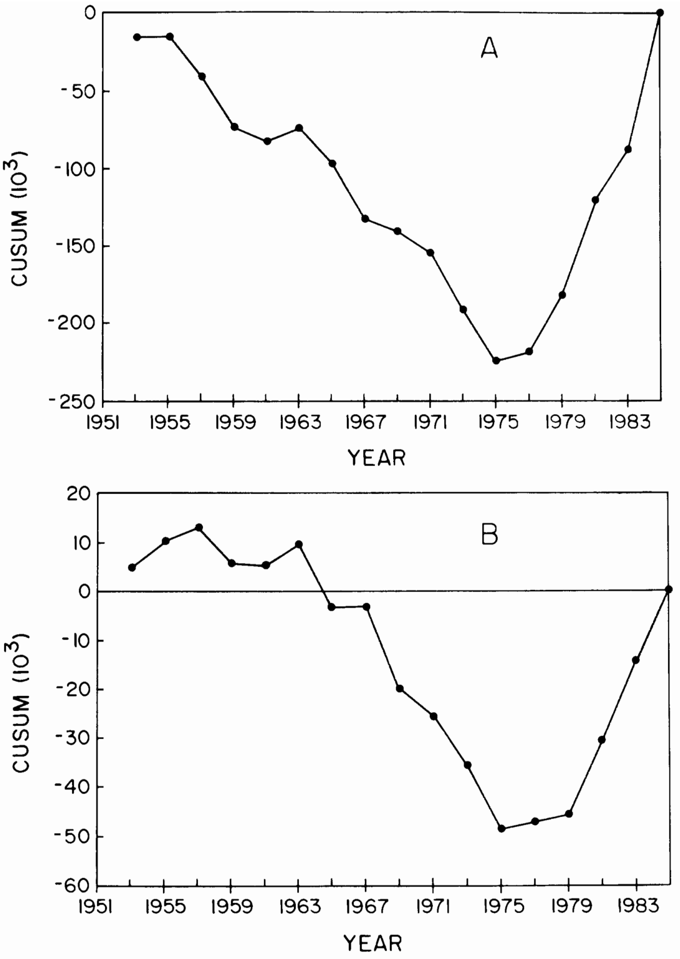

FIG. 17. A. Cumulative sum of the odd-year pink salmon catch (t) by (A) the United States, 1952–85, and (B) Canada, 1952–85 (INPFC 1979, 1977–89). Abundance trends in catch of both countries are similar from the early 1960s.

If odd-year catches are examined separately, there was an increase in catch in both countries beginning in 1977 (Fig. 17). Again, the response was much larger in the United States in Alaska.

Even-year catches (Fig. 18A) were more variable than odd-year catches, and trends were different between Canada and the United States (Fig. 18B, 18C). The CuSum chart indicates that catch trends in the United States had four distinct trends from 1952 to 1984. From 1952 to 1960 the mean catch was 36.0×10^3 t, while from 1961 to 1968 the mean catch increased to an average of 60.6×10^3 t. Mean catch declined to 35.7×10^3 t from 1970 to 1976 and increased dramatically to 101.8×10^3 t beginning in 1978.

The catch trends off the west coast of Canada for even-year spawning stocks were similar except there was not an increase in average catch starting in 1978 (Fig. 18C). The decline in average catch that started about 1970 in both the United States and Canada continued in Canada through to 1984 (Fig. 18C).

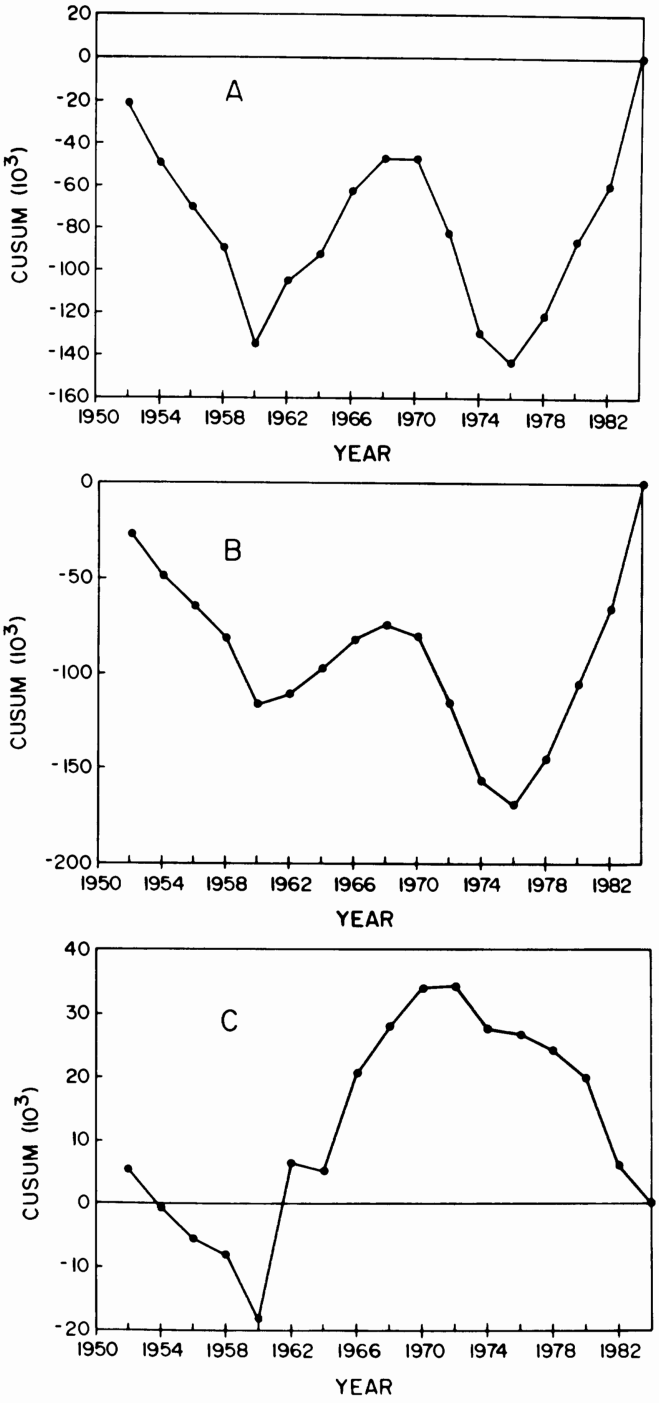

FIG. 18. (A) Cumulative sum of the even-year pink salmon catch (t) by Canada and the United States, 1952–85. The abundance trends are similar to the odd-year trends except during the 1960s. (B) Cumulative sum of the even-year pink salmon catch (t) by the United States, 1952–85. (C) Cumulative sum of the even-year pink salmon catch (t) by Canada, 1952–85. The abundance trends in the Canadian catch do not show the increasing trend in the late 1970s. (Data from INPFC 1979, 1977–89.)

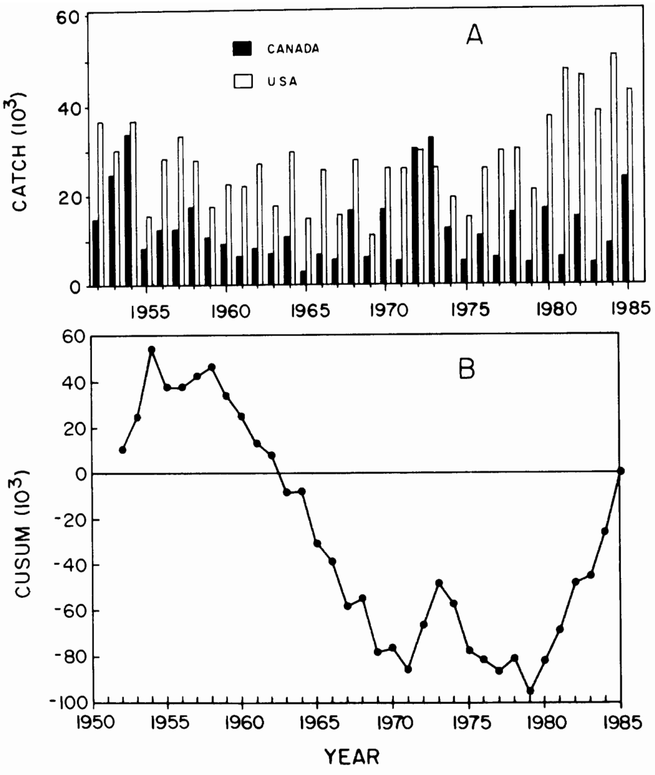

FIG. 19. (A) Chum salmon catch (t) by country and (B) cumulative sum of the chum salmon for the combined catch (t) by Canada and the United States, 1952–85 (INPFC 1979, 1977–89).

Chum Salmon (*Oncorhynchus keta*)

Chum salmon are the latest of the salmon to spawn, although some may enter streams in early summer and spawn in summer. After hatching and emerging from the gravel in the spring, the fry migrate directly to sea. Juvenile chum salmon have the widest natural distribution of all Pacific salmon species (Fredin et al. 1977).

The highest percentage of maturing adults return after spending 3 yr at sea or 4 yr after eggs are fertilized. Adults can range in age from 2 to 7 yr (Salo 1991), but most are 3-5 yr old (from spawning) when they return to spawn. Thus, most of the fish that returned in 1980 as 4-yr-olds were spawned in 1976 and went to sea in 1977.

Annual catches in the United States were about double the Canadian catches in most years (Fig. 19A). The mean total catch from both countries from 1958 to 1971 was 31.5×10^3 t without large fluctuations in the CuSum chart (Fig. 19B). There was an increase in the mean catch in 1972 and 1973, followed by a decrease in the mean from 1974 to 1979 (Fig. 19B). The trend in the mean catch increased abruptly in 1980. The shape of the CuSum chart for catches in the United States was similar to that for sockeye and pink salmon catches in the United States fishery. In the Canadian fishery, catch trends were similar to the United States fishery up to 1971; there was an increase in catch from 1972 to 1973 and a decline from 1974 to 1984. There was no increase in mean catch beginning in 1980 as was observed in the United States fishery.

Chum salmon returning in 1980 were the 1976 brood year that went to sea in 1977. The change in catch trends that occurred in the Alaskan fishery in 1980 is another indication that, in general, 1977 was a year of above-average marine survival for salmon. The absence of a response by Canadian stocks may indicate that improved survival of chum salmon occurred initially in the more northern areas of their distribution.

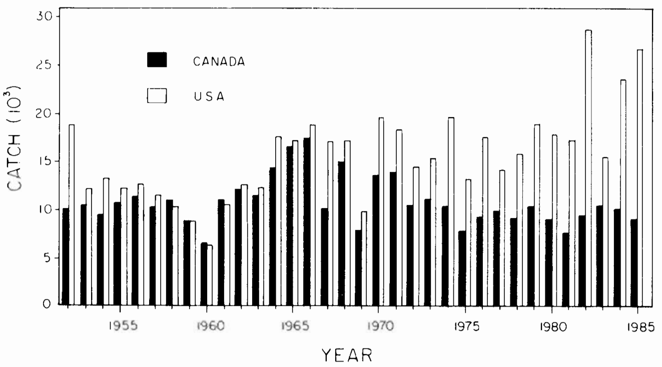

FIG. 20. Coho salmon (t) by country (INPFC 1979, 1977–89).

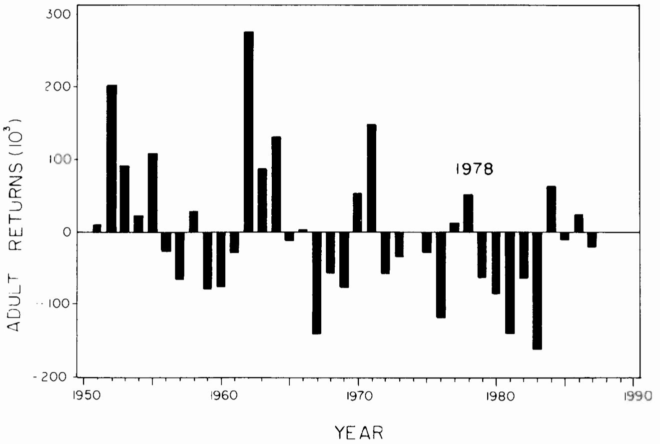

FIG. 21. Anomalies from the long-term mean of returns of wild-spawning coho salmon to the Fraser River (data courtesy of K. Wilson and R. Kadowaki, Pacific Biological Station, Nanaimo, B.C.).

Coho Salmon (*Oncorhynchus kisutch*)

Coho salmon are distributed along the coast of North America from California to Alaska and into the Bering Sea (Hart 1973). Eggs are deposited in the fall and hatch the following spring, with most fry remaining in streams for 1 yr before entering the sea. Juveniles remain at sea for an average of 18 mo. Most coho salmon are therefore age 3 when they spawn and die in fresh water.

Catches of coho salmon in the Canadian and United States fisheries from 1952 to 1985 (Fig. 20) were similar until 1970, after which United States catches increased and Canadian catches declined slightly. Canada and the United States have extensive enhancement programs that contributed an increasing number of coho salmon to the fishery beginning in the mid-1960s in the United States and mid-1970s in Canada. Because of the complexity of separating hatchery catches from wild catches and of interpreting the impact of the hatchery program on wild coho salmon population dynamics, I have not used total catches of coho salmon to examine trends in abundance. Instead, I looked at returns from some of the major Canadian coho salmon fisheries.

In British Columbia, more coho salmon are produced in the Fraser River than in any other system. Coho salmon that went to sea in 1977 were from the 1975 spawning or brood year and returned to spawn in 1978. The total returns (catch plus spawners) from the 1975 brood year were above average relative to the average returns since 1951 (Fig. 21). Except for the returns from the 1981 brood year, the returns from coho that went to sea in 1977 were the highest wild returns over the period 1971–87. The returns from the 1981 brood year were similar to the returns from the 1975 brood year.

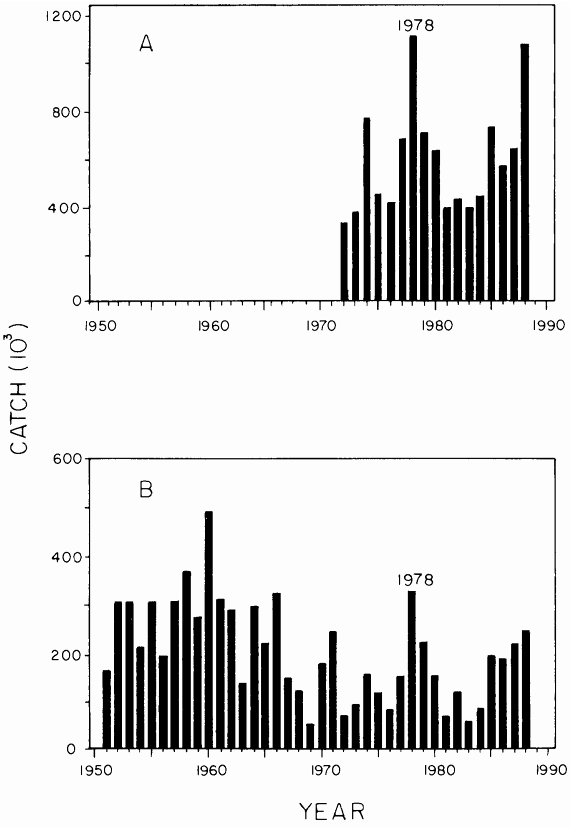

FIG. 22. (A) Sports catch and (B) troll catch of coho salmon in the Strait of Georgia (data courtesy of K. Wilson and R. Kadowaki, Pacific Biological Station, Nanaimo, B.C.).

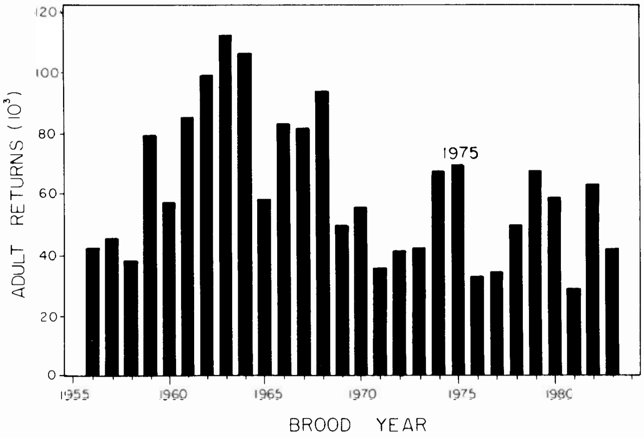

FIG. 23. Total return (catch + escapement) of age 3 coho salmon to the Skeena River (from Kadowaki 1988), by brood year. Most fish from the 1975 brood year went to sea in 1977.

The increase in survival of the 1975 brood year is also reflected in the coho salmon catch in the sports fishery and the commercial troll fishery in the Strait of Georgia in 1978. The sports catch in 1978 was the highest over the period 1972–88 (Fig. 22A). Similarly, the commercial troll catch was the highest on record over the period 1967–88 (Fig. 22B).

In the Skeena River, coho salmon spend 1 or 2 yr in fresh water

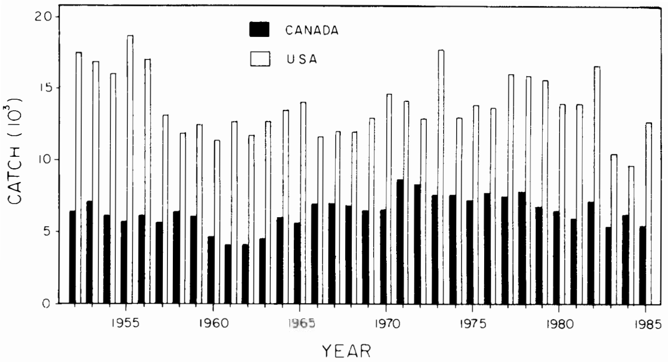

FIG. 24. Chinook salmon catch (t) by country (INPFC 1979, 1977–89).

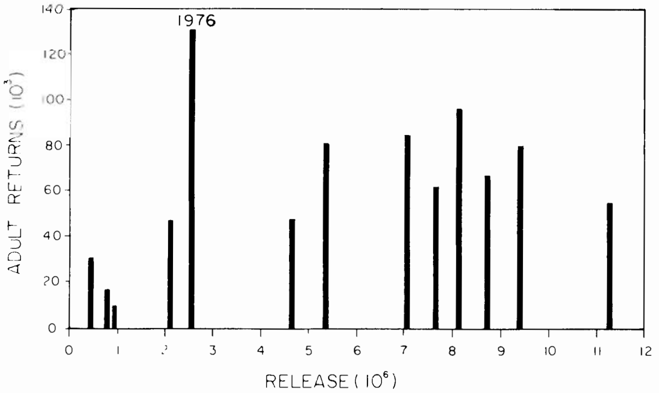

FIG. 25. Releases and returns of chinook salmon from hatcheries in the Strait of Georgia, 1972–85 (data from Beamish et al. 1992). Releases are recorded for brood years. The fish from the 1976 brood year went to sea in 1977.

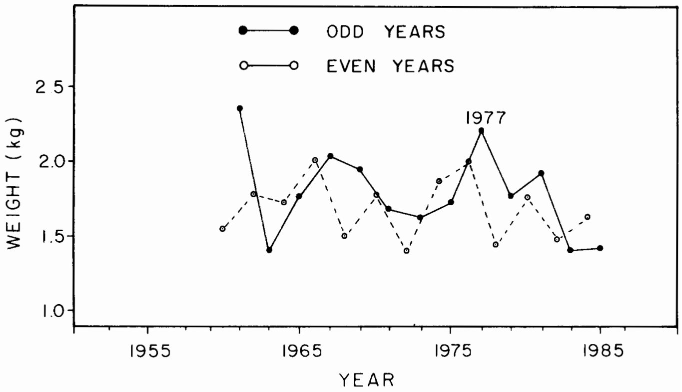

FIG. 26. Average weight of pink salmon caught in the fishery in southeast Alaska (data courtesy of W.E. Ricker, Nanaimo, B.C.). The trend of declining size changed briefly beginning in 1977.

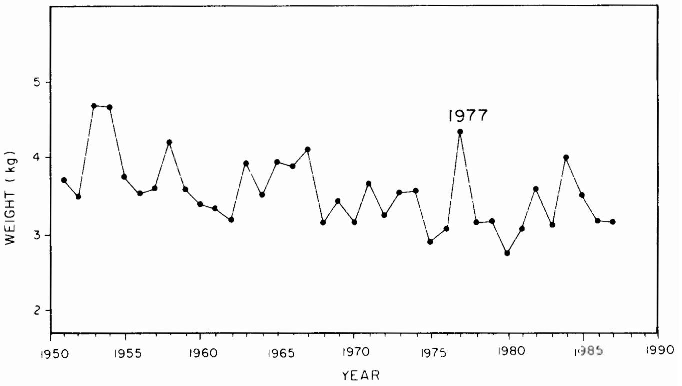

FIG. 27. Average weight of coho salmon caught by the troll fishery in the northern coast off the Queen Charlotte Islands, B.C. (data courtesy of W.E. Ricker, Nanaimo, B.C.).

after hatching, returning to spawn in their third or fourth year after 18 mo in the marine environment. The dominant age class on return are 3-yr-old fish that have spent 2 yr in fresh water. Consequently, coho that went to sea in 1977 and returned in 1978 would be predominantly the 1975 brood year with a smaller component from the 1974 brood year. The total returns from the 1975 and 1974 brood years were above average for the returns of all brood years over the period 1969–83 (Fig. 23).

Chinook Salmon (*Oncorhynchus tshawytscha*)

Chinook salmon have the most complicated life history of the five salmon species found in British Columbia. In general, there are two life history types, the ocean type and the stream type. The ocean-type fish spawn in the fall and go to sea the following spring. Chinook salmon raised in hatcheries are all ocean type. Stream type spawn in the fall and remain in the spawning stream for 1 yr. When returning to spawn, stream type generally arrive earlier than the ocean type. Most chinook salmon return to spawn from age 3 to 5 (Healey 1991).

Catches of chinook salmon in the United States and Canadian fisheries were more constant than the catches of other salmon from 1952 to the early 1980s (Fig. 24), with catches in the United States always larger than Canadian catches (Fig. 24). Chinook salmon catches, like coho salmon catches, were influenced by hatchery programs. Catch information, therefore, is not necessarily a good indicator of abundance trends. Also, because of the complex life cycle of the chinook salmon, the very limited amount of age information available, and the complexities of the fisheries, it is difficult to study the relative success of year classes. It is possible, however, to examine the survival of chinook salmon that were released from hatcheries. Hatchery releases in Canada indicate that chinook salmon that went to sea in 1977 had increased survival. The returns from hatcheries that released smolts into the Strait of Georgia were the highest in the 1977 release year even though the number of smolts released increased after 1977 (Fig. 25).

Growth of Maturing Salmon during 1977

The average size of pink and coho salmon has declined since 1950 (Ricker et al. 1978; Ricker and Wickett 1980). There were annual fluctuations in the average size of fish caught in the various fisheries, but there was no doubt that a decrease in mean size occurred. The analyses have recently been extended (W.E. Ricker, Pacific Biological Station, Nanaimo, B.C., unpublished data) to the late 1980s. In many fisheries, the decline in average weight continued. However, in 1977 there was clear evidence that the size of salmon in the commercial catches was anomalously large for pink, coho, and chinook salmon. For pink salmon the increase in size was particularly evident for the odd-year spawning stocks in southeastern Alaska and northern British Columbia (Fig. 26). Because pink salmon grow most during their second year in salt water, it is evident that feeding conditions

TABLE 1. Landings from the major fisheries off the west coast of Canada and the United States for 1988. The landings for salmon are the average annual landings from 1983 to 1986. The category of others includes rockfish, flatfish, and other "minor" species. n/a, not applicable because no fishery exists.

Species	Canadian landings (t)	U.S. landings (t)	Total (t)
Pink salmon	24 567	116 502	141 069
Sockeye salmon	23 962	108 921	132 883
Chum salmon	15 570	45 469	61 039
Coho salmon	10 438	24 915	35 353
Chinook salmon	5 855	12 916	18 771
Pacific herring	30 998	67 533	98 531
Pacific halibut	4 762	26 850	31 612
Walleye pollock	577	1 283 423	1 284 000
Pacific cod	10 835	228 665	239 500
Pacific hake	90 491	170 688	261 179
Northern anchovy[a]	n/a	84 887	84 887
Chub mackerel	n/a	54 671	54 671
Sablefish	5 196	43 854	49 050
Pacific ocean perch	6 673	16 124	22 797
Lingcod	2 508	2 976	5 484
Yellowtail rockfish	4 778	6 263	11 041
Widow rockfish	2 065	10 891	12 956
Atka mackerel	n/a	30 061	30 061
Others	19 534	295 887	315 421
Total	258 809	2 631 496	2 890 305

[a] Includes catches off Mexico.

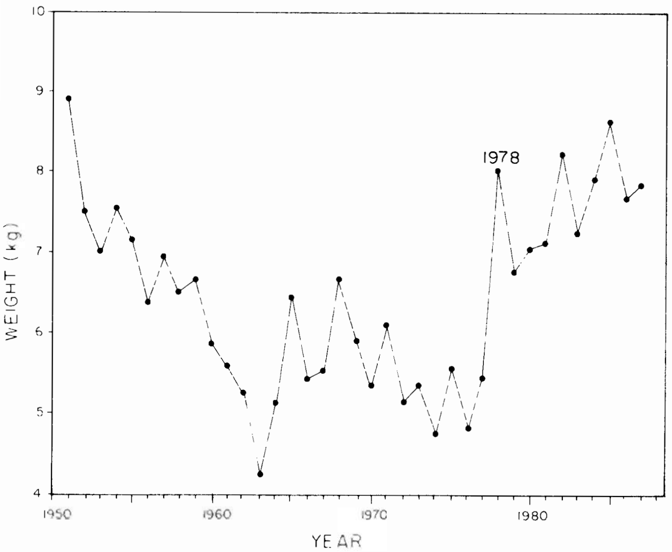

FIG. 28. Average weight of chinook salmon caught in the Kitimat-Butedale area troll fishery (data courtesy of W.E. Ricker, Nanaimo, B.C.). The trend of declining sizes changed abruptly in 1978.

were above average in 1977. Most coho salmon also return to spawn after their second year in salt water. It is during this second year, the year in which they are captured by the commercial fishery, that they increase most in weight. In 1977, in 33 of 42 fisheries, coho salmon were much larger than in adjacent years (Fig. 27). These increases in size occurred mostly in the north and not in many of the southern areas or in Puget Sound.

W.E. Ricker (unpublished data) also identified 1978 as a year that produced large chinook salmon. Because chinook salmon are taken by troll over a much longer season than pink or coho salmon, they will have undergone most of their growth in the calendar year before capture in 1977 (Fig. 28). W.E. Ricker (unpublished data) identified a decreasing trend in average sizes of chinook salmon from 1951 to 1975 in 18 of 19 areas from southeast Alaska to Puget Sound. Starting in 1977 or 1978, the trend changed and the average size increased (Fig. 28 shows one of the more extreme changes in trend). This change first appeared in northern stocks, with some southern stocks showing the increasing trend by about 1983. Some southern stocks have not increased in average size.

W.E. Ricker (unpublished data) identified nine possible causes of the trends in size changes, including a change in the ocean environment that would affect growth rate, age at maturity, or both. The cause of the growth rate changes remains a mystery, but the synchronous nature of the trends in the late 1970s indicates both an association with the ocean environment and that food for these salmon species was abundant in 1977. The increased growth and the increased survival indicate that there must have been an increase in marine carrying capacity for these species of salmon in 1977.

Nonsalmon Fisheries

Changes in the abundance of nonsalmon fisheries were examined for fishes that contributed to commercial fisheries and had a reliable time series of catch or other biological information beginning before the mid-1970s. The following accounts of strong year-class production exclude examples of fisheries that did not show increases in productivity in the late 1970s, but these fisheries, identified as "others" in Table 1, represented only a small percentage (11%) of the total catch (Table 1). I used published data to develop indices of year-class strength and combined these indices using the method described by Ebbesmeyer et al. (1991) to show that there was a synchronous increase in year-class survival from 1976 to 1978. In the following species

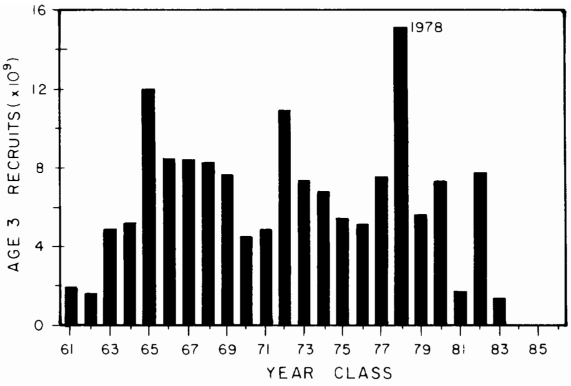

FIG. 29. Calculated number of age 3 walleye pollock in the eastern Bering Sea using surface otolith age estimates (from Wespestad and Traynor 1987).

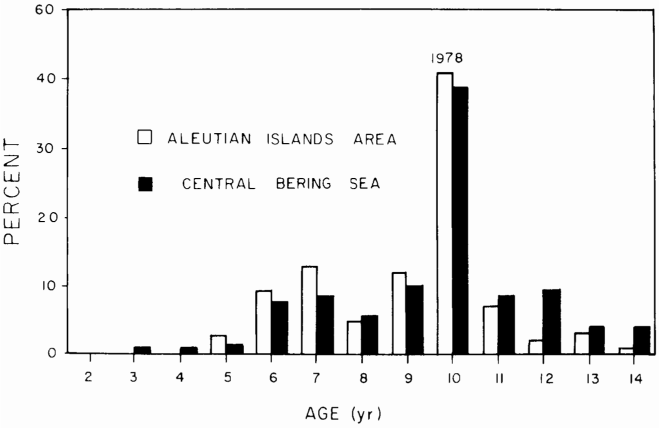

FIG. 30. Age composition of commercial walleye pollock catches in 1988 within the United States 200-mile zone in the Bering Sea showing the strong 1978 year class; ages estimated from otolith surfaces (from Dawson 1988).

summaries, I briefly describe the biology and present relevant fisheries information to show the extent and diversity of the response. At the end of the species accounts, I combine the year-class strength indices to show that there was a synchronous increase in survival for most species about 1977.

Walleye Pollock (*Theragra chalcogramma*)

Walleye pollock spawn in the midwater or just off bottom from late February until late May. Most spawning occurs in early April. There may be more than one spawning event in some areas, resulting in several pulses of spawning (Bulatov 1988; Haldorson et al. 1988). The pelagic larval walleye pollock move from near the bottom after hatching to a depth of about 50 m (Kim 1988). At this time, copepod nauplii are the most important food for larvae smaller than 14 mm (Kendall et al. 1987). Larger larvae concentrate near the surface in late May and feed on adult copepods (Kendall et al. 1987). In Auke Bay, Alaska, maximum abundance of larval walleye pollock in the surface waters occurred at the time of maximum abundance of herbivorous copepods (Haldorson et al. 1988). Age 2 and age 3 fish are taken in the fishery, but full recruitment is not considered to occur until age 4.

A reconstruction of year-class strength, using age estimates from otolith surfaces, identified the 1978 year-class as the strongest on record in the Bering Sea (Fig. 29), and it still dominates the United States commercial catch (Fig. 30). In the western Bering Sea, both the 1977 and 1978 year classes were thought to be very large (Moiseyev 1983). It is possible that both year classes were strong, but it is also probable that errors in determining age resulted in fish from one strong year class being assigned to other age classes. A review of possible aging errors (McFarlane and Beamish 1990) indicated that ages determined from examinations of the otolith surface could underestimate the actual age of some stocks of walleye pollock. The new ages produced by the method suggested by McFarlane and Beamish (1990) indicated that more age groups existed in samples from commercial fisheries than previously thought.

The new interpretation of age was used to estimate the age of

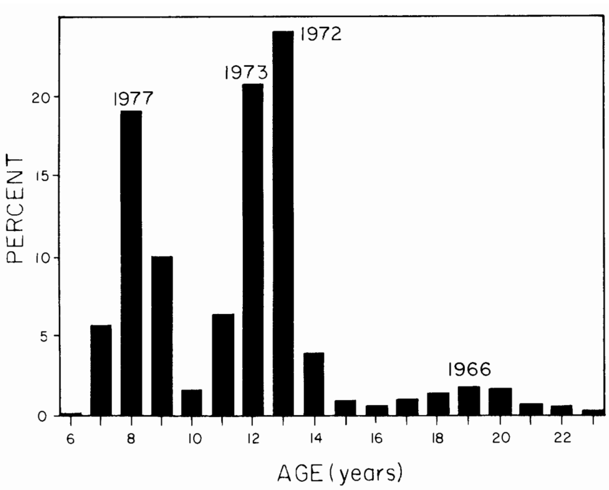

FIG. 31. Age composition of walleye pollock sampled in February 1985 by Polish scientists in the international area of the Bering Sea (n = 299). Abundance of age groups was determined using an age–length key to convert length–frequency distributions to age–frequency distributions. Relative year class strength is in percent. Ages determined using the method of McFarlane and Beamish (1990).

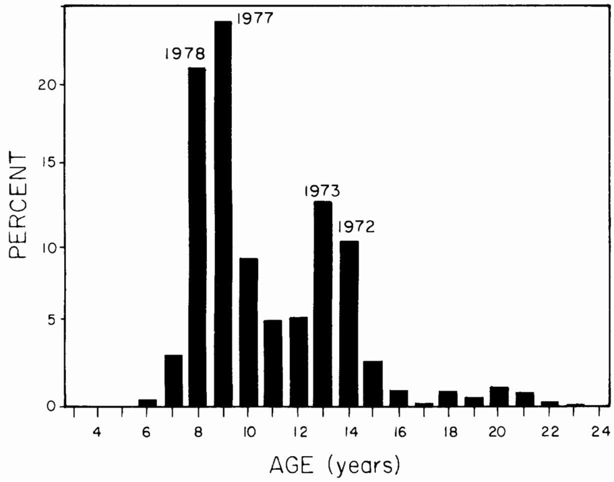

FIG. 32. Age composition of walleye pollock sampled from January to April 1986 by Polish scientists in the international area of the Bering Sea (n = 1600). Abundance of age groups was determined using an age–length key to convert length–frequency distributions into age–frequency distributions. Relative year class strength is in percent. Ages determined using the method of McFarlane and Beamish (1990).

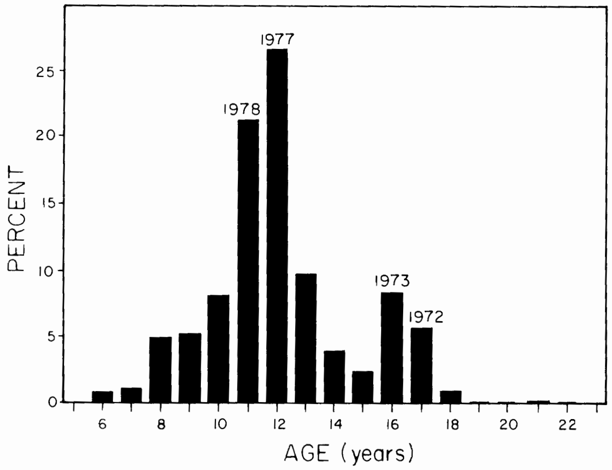

FIG. 33. Age composition of walleye pollock sampled from January to April 1989 by Polish scientists in the international area of the Bering Sea (n = 1201). Abundance of age groups was determined using an age-length key to convert length-frequency distributions to age-frequency distributions. Relative year class strength is in percent. Ages determined using the method of McFarlane and Beamish (1990).

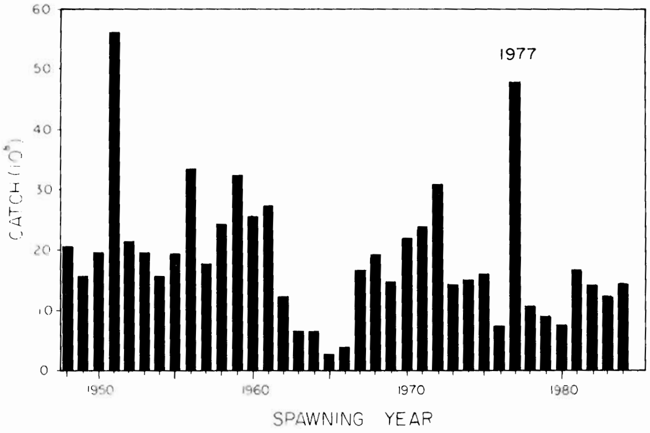

FIG. 34. Calculated number of age 2+ Pacific herring in the population by spawning year (Haist et al. 1988).

walleye pollock caught in the Polish commercial fishery in the Bering Sea in 1985 (data provided by Dr. J.F. Janusz, Sea Fisheries Institute, Gdynia, Poland). Because this sample was obtained at the beginning of the fishery, it represents the age composition of a relatively unexploited population. In 1985, 299 fish were aged from a sample collected from January to April (Fig. 31) and 1600 fish were aged from a sample collected in the same period in 1986 (Fig. 32). Both the 1985 and 1986 samples indicated that very strong year classes occurred around 1965 and 1966, 1972 and 1973, and 1977 and 1978. The age composition of the 1989 Polish catch (Fig. 33) shows that the 1977 and 1978 year classes are still important, indicating that an exceptionally strong year class or year classes occurred about 1977. Because the walleye pollock fishery is extremely large, the exceptionally strong year classes produced around 1977 and 1978 represent a large increase in fish biomass.

Pacific Herring (*Clupea pallasi*)

The Pacific herring fishery is one of the oldest fisheries in British Columbia and was also the largest in British Columbia from 1955 to 1967. The fishery shut down in the late 1960s and resumed again in the early 1970s. Currently the fishery harvests about 35 000 t for a roe market. Herring catches off the coast of Alaska are currently larger than off the coast of British Columbia, but historically, catches in the herring fishery off the coast of Alaska were less than one half of those in British Columbia. Most herring in the Alaska fishery range from 4 to 12 yr and in British Columbia from 2 to 5 yr.

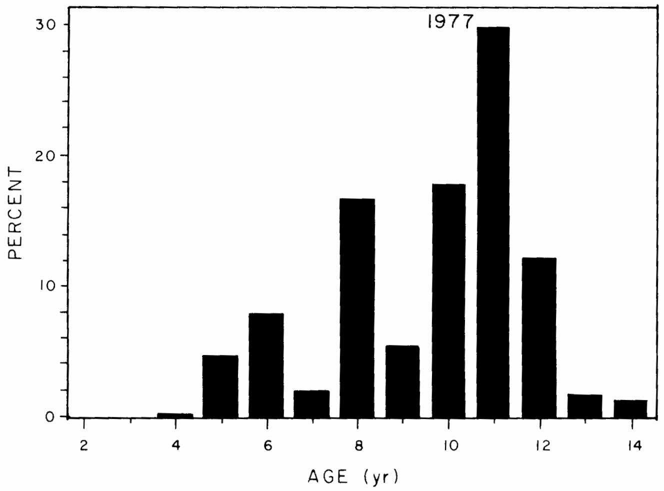

FIG. 35. Age composition of the 1988 catch of Togiak District Pacific herring showing the strong 1977 year class (from Funk and Savikko 1989).

The relative abundance of age 2+ herring in the Canadian fishery was estimated from 1948 to 1984 using an age-structured model (Haist et al. 1988). The abundance of age 2 herring from the 1977 spawning was the second strongest year class on record (Fig. 34). Off the Alaskan coast, strong year classes in the five largest stocks, representing 90% of the catch, were produced in 1977 (Funk and Savikko 1989). Strong year classes were also reported in some Alaskan stocks in 1976 and 1978. In the Togiak stock in Alaska the strong 1977 and 1978 year classes still dominated catches in 1988 (Fig. 35).

Pacific Cod (*Gadus macrocephalus*)

The centre of abundance of Pacific cod is off the coast of Alaska, in the eastern Bering Sea. In British Columbia, they are close to the southern limit of their commercial abundance. Pacific cod grow rapidly and are fully recruited into the fishery by age 3. Few fish survive to age 7 in the Canadian fishery. Older fish occur in the fishery off Alaska; however, stock assessment models assume a maximum age of 8 yr in the catch (Zenger and Thompson 1989a). Zenger and Thompson (1989a) estimated that from 1975 to 1985, in the eastern Bering Sea, the 1977 year class had exceptional production as indicated by age 3 individuals (Fig. 36). A strong 1976 year class was also identified. However, Pacific cod can be difficult to age (Beamish et al. 1990), making it possible that aging error contributed to the appearance that both the 1976 and 1977 year classes were strong.

In the Gulf of Alaska, the 1977 year classes dominated the fisheries in the early 1980s (Zenger and Thompson 1989b). Zenger and Thompson (1989b) did not provide the age composition of the catch because it "has proven to be a frustrating task." However, using age 3 as the age of recruitment, it appears that the more than doubling of the catch in 1980 compared with 1978 and 1979 is the result of a strong 1977 year class.

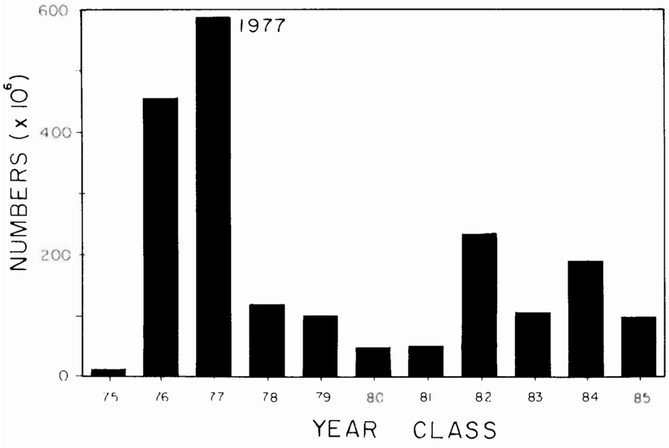

FIG. 36. Estimated number of age 3 Pacific cod recruited into the fishery in the eastern Bering Sea from 1975 to 1985 (from Zenger and Thompson 1989a).

Age estimates have not been determined for the Canadian commercial fishery for Pacific cod in the late 1970s and early 1980s. However, an index of the size of the Hecate Strait population indicated that a significant increase in survival occurred in 1977 (Tyler and Westrheim 1986).

Pacific Halibut (*Hippoglossus stenolepis*)

Pacific halibut is one of the most important commercial bottom fish off the west coast of North America. The centre of abundance of Pacific halibut is in the Gulf of Alaska and in the northern waters off the coast of British Columbia. Reliable estimates of the age composition of the catch in the commercial fishery exist from 1923, making this data series one of the longest of all west coast fisheries. Pacific halibut are first recruited to the fishery at age 8 and fully recruited by age 11. The International Pacific Halibut Commission publishes the age composition of commercial catches. In 1988, the catch consisted of a large number of age 11 fish, from the 1977 year class. When the catch of age 11 fish is compared with the catches of similar aged fish, it is apparent that the 1977 year class was exceptionally strong (Fig. 37). The 1977 year class remained the dominant age class in the fishery into the early 1990s (International Pacific Halibut Commission, Seattle, WA 98145-2009, unpublished data). Beginning in 1986, recruitment of 8-yr-olds declined (International Pacific Halibut Commission, unpublished data), indicating that year class strength declined after 1977.

Pacific Ocean Perch (*Sebastes alutus*)

Pacific ocean perch was historically the most important species of rockfish in the Canadian and United States fisheries. Pacific ocean perch give birth along the coast from California to the eastern Bering Sea from January to March. They are long-lived and are not recruited into the fishery until age 8–11. As a result of extensive foreign fishing for Pacific ocean perch off the west coast of North America from the mid-1960s until the late 1970s, catches declined dramatically in this period. In the Gulf of Alaska, for example, catches were as high as 350 000 t in 1965 but declined to about 5500 t after 1977 (Balsiger et al. 1985). Reliable age estimates are available from the late 1970s. Prior to this, age determinations seriously underestimated the actual age of many fish caught in the fishery (Beamish 1979). Strong year classes were produced off the coast of Canada, in the Gulf of Alaska (Fig. 38), and in the Bering Sea in 1976 (Fargo and Tyler 1989; Ito 1989; Ronholt 1989; Heifetz and Clausen 1992). It is possible that 1976 may not be the correct year of the strong year class because of aging errors, but a strong year class clearly was produced about this time.

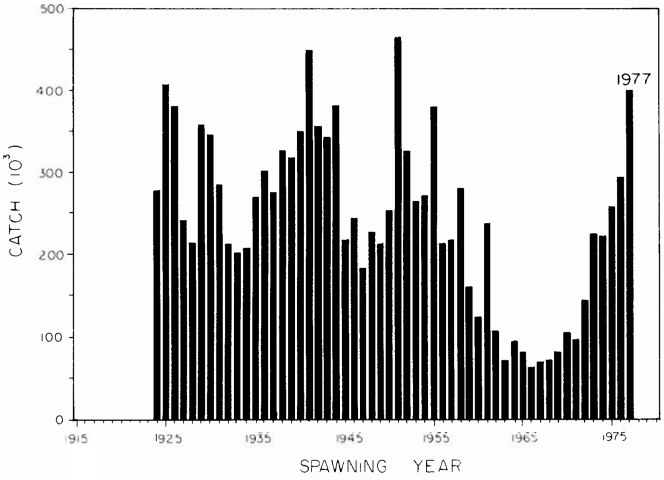

FIG. 37. Calculated number of age 11 Pacific halibut in the commercial catch (data from the International Pacific Halibut Commission).

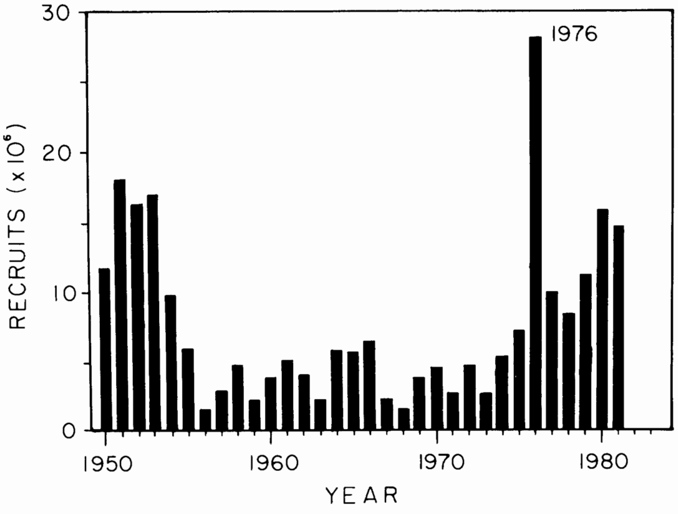

FIG. 38. Estimate of age 9 Pacific ocean perch in the Gulf of Alaska population (Heifetz and Clausen 1992; data from J. Heifetz, Auke Bay Laboratory, Juneau, Alaska).

Yellowtail Rockfish (*Sebastes flavidus*)

Yellowtail rockfish are most abundant off the coasts of southern British Columbia, Washington, and Oregon. Yellowtail rockfish are slow growing and long-lived; the oldest recorded age is 64 yr (Chilton and Beamish 1982). They are first captured at about age 5 and are fully recruited at age 14 (Tagart 1988). In Canada, the total landings in 1988 were 5100 t, including 334 t of incidental catch in the offshore Pacific hake (*Merluccius productus*) fishery. This was the second largest rockfish fishery, accounting for 18.5% of the total rockfish catch. In the United States, 1988 landings totalled 6263 t, of which 89% was from waters off the coasts of Washington, Oregon, and northern California.

In 1986, 9-yr-olds (the 1977 year class) dominated the age groups in the Canadian catch. In 1988, the 1977 year class still

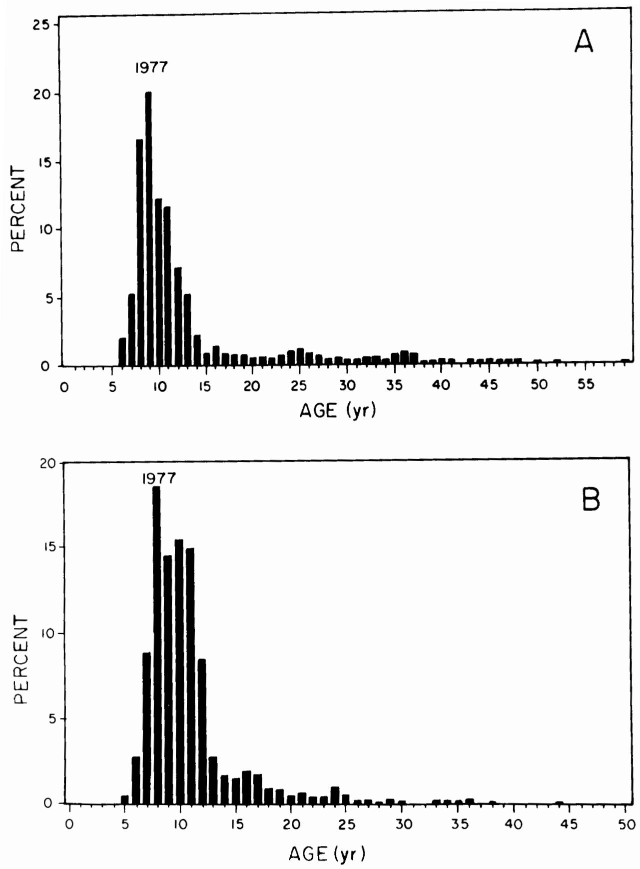

FIG. 39. (A) Age composition of yellowtail rockfish caught in Queen Charlotte Sound in 1986 showing the strong 1977 year class (data courtesy of R. Stanley, Pacific Biological Station, Nanaimo, B.C.) and (B) estimated yellowtail rockfish in the catch by age off Washington in 1985 (from Tagart 1988).

continued to dominate age groups in the catch (Fig. 39A). In the United States, the strong 1977 year class appeared in catches off the coast of Washington (Fig. 39B) but not farther south (Tagart 1988).

Widow Rockfish (*Sebastes entomelas*)

Widow rockfish is a valuable species in the rockfish catch off the coasts of Washington, Oregon, and California. In 1987, these catches totalled 12 185 t (Lenarz and Hightower 1988). In 1988, catches off the west coast of Canada were 2065 t. Because they are long-lived, with a maximum age of 58 yr (Chilton and Beamish 1982), the age at full recruitment is probably 8–11 yr, similar to other long-lived rockfish species. The age at first capture is 4 yr; thus the 1977 year class would not appear in the catches until 1981. Lenarz and Hightower (1988) estimated the total number of widow rockfish for each year class caught by the fishery from 1980 to 1987. In 1984, the 1977 and 1978 year classes dominated the catch (Fig. 40). The estimated age composition of the 1987 catch indicated that the 1977 and 1978 year classes were still strong and that the production of widow rockfish increased from 1977 into the 1980s (Lenarz and Hightower 1988).

Atka Mackerel (*Pleurogrammus monopterygius*)

Atka mackerel are found along the continental slope off the United States and Russia in the northern North Pacific Ocean and the Bering Sea, with the centre of abundance along the Aleutian Islands. Age at recruitment is 3 yr (McDevitt 1989) and most fish in the fishery are less than 13 yr old (McDevitt 1989). Catches within the United States 200-mile limit were at record levels from 1984 to 1987, averaging 34 000 t. The catch dropped slightly in 1988 to 30 061 t.

The strong 1977 year class first appeared in the catch in 1980 at age 3, accounting for 52% of the age classes in the catch (Fig. 41A). The 1977 year class dominated the catch in 1982 when it was 78% of the numbers landed and 69% of the total weight (Fig. 41A). In 1987, even though a strong 1984 year class entered the fishery, the 1977 year class represented 17% of the catch by number and 21% of the catch by weight (Fig. 41B).

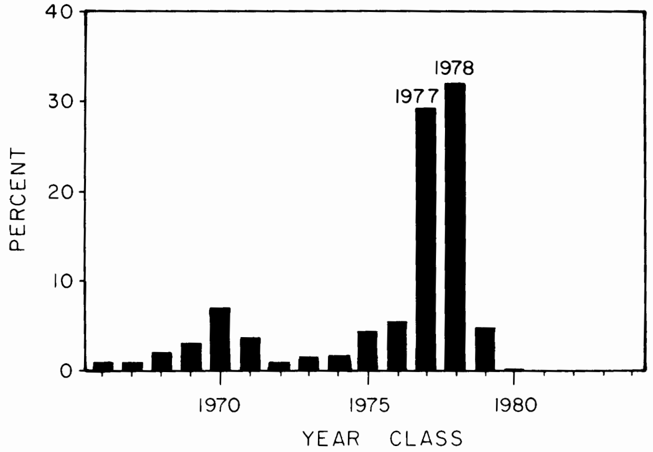

FIG. 40. Widow rockfish catch by year class in 1984 (from Lenarz and Hightower 1988). Year classes prior to 1966 were not included because of their low relative abundance.

Sablefish (*Anoplopoma fimbria*)

The sablefish fishery occurs off the coasts of California, Oregon, and Washington and is most important off the coast of British Columbia and in the Gulf of Alaska. In recent years, this fishery in Canada has become the most valuable Canadian groundfish fishery. Sablefish spawn in mid-February and are long-lived (Beamish and Chilton 1982). They are recruited to the fishery about age 5 and can live for over 60 yr. Recent age estimates and length frequency distributions indicate that an exceptionally strong year class occurred in 1977 throughout most of the spawning range (McFarlane and Beamish 1983; Sigler and Fujioka 1988). The 1977 year class was so strong that it dominated the age composition of catches well into the 1980s (Fig. 42). Other strong year classes occurred in the late 1950s and early 1940s (McFarlane and Beamish 1992). Strong year classes in general and the 1977 year class in particular were recently shown to be significantly related to coastwide increases in copepod production (McFarlane and Beamish 1992).

Pacific Hake (*Merluccius productus*)

Pacific hake occur off the coasts of California, Oregon, Washington, and British Columbia. The Canadian Pacific hake fishery lands the largest catch, by weight, of any species in the Canadian fishery. Pacific hake caught in the fishery off Canada are part of an offshore population that spawns off the coasts of California and Mexico, mainly during January and February (Alverson and Larkins 1969). This offshore population has been fished commercially for approximately 25 yr. Current abundance

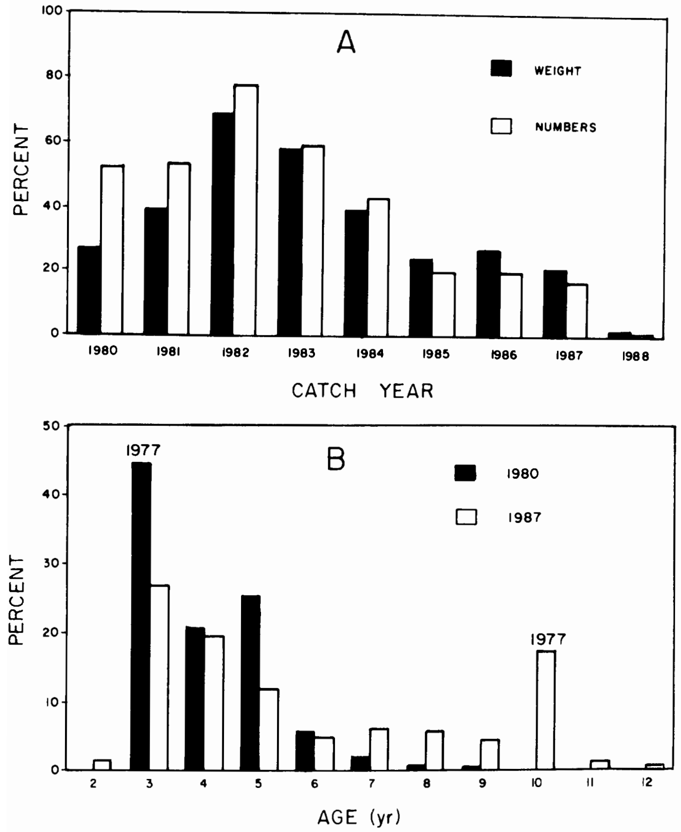

FIG. 41. (A) Percent by number and weight of the 1977 year class of Atke mackerel in catches from 1980 to 1988 (from McDevitt 1989) and (B) estimated age of catch of Atka mackerel in the Aleutian Islands region for 1980 and 1987 (from McDevitt 1989).

estimates vary but appear to average about 1 250 000 t (Francis 1983).

Eggs and newly hatched larvae are found at depths of 40–100 m. Larvae feed on copepod eggs and nauplii, and adults feed heavily on euphausiids. Juveniles mature at age 3. They are recruited into the fishery from age 3 to age 6. Older and larger fish migrate into the Canadian zone in late spring and early summer and return to spawn in the fall. Because mature females are larger than mature males, more females are captured in the fishery off Canada than males.

The presence of strong year classes is a common feature of the offshore population (Bailey and Francis 1985). Dorn and Methot (1989) calculated that strong year classes occurred in the fishery in 1970, 1973, 1977, 1980, and 1984 (Fig. 43). These strong year classes dominated the age composition of the catch in the fishery off Canada. Although the 1977 year class was not as strong as some others, it was still abundant in the Canadian fishery in the late 1980s (Fargo et al. 1988).

Chub Mackerel (*Scomber japonicus*)

Most chub mackerel occur off the coast of California where spawning occurs inshore at depths to 92 m from late April to July (MacCall and Prager 1988). Females may spawn more than once during this period. The maximum age is 9 or 10 yr, but most fish are fully recruited into the fishery at age 4 (MacCall et al. 1985). The chub mackerel fishery in the United States started in 1929, but collapsed in the late 1960s, and in 1970 the California fishery was closed (Parrish and MacCall 1978). It reopened in 1977

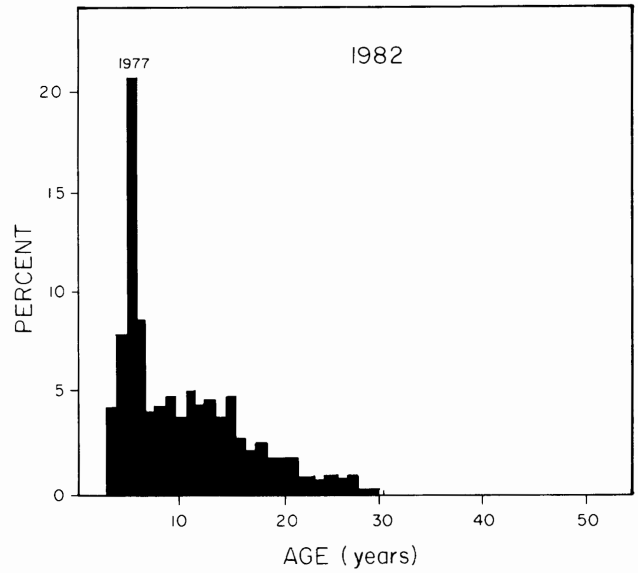

FIG. 42. Age composition of the commercial catch of sablefish in 1982 from the west coast of Canada (from Fargo et al. 1988).

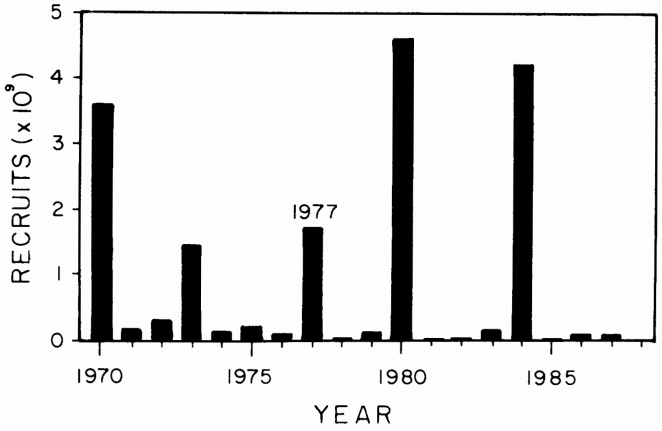

FIG. 43. Estimated number of age 2 Pacific hake determined from cohort analysis that would be recruited into the fishery from each of the year classes (from Dorn and Methot 1989).

when abundance appeared to be increasing. Total United States and Mexico catches increased from 4064 t in 1976–77 to 42 361 t in 1981–82 (MacCall et al. 1985).

Chub mackerel abundance from 1977 to 1984 was the highest in almost 50 yr (MacCall et al. 1985). The 1976 year class was produced from a very small population of adults, but the strongest year class was produced in 1978 (Fig. 44). This year class was the largest on record 27–52% larger than the previous record, the 1932 year class. Three of the four largest year classes in the history of the fishery were produced in 1978, 1980, and 1981 (Fig. 44).

Lingcod (*Ophiodon elongatus*)

The fishery for lingcod is one of the oldest in British Columbia (Cass et al. 1990). Most lingcod are recruited to the fishery between age 5 and age 6. Maximum age is believed to be 21 yr (Chilton and Beamish 1982). Because a method to determine the age of lingcod was only recently developed (Beamish and Chilton 1977; Cass and Beamish 1983), there are relatively few

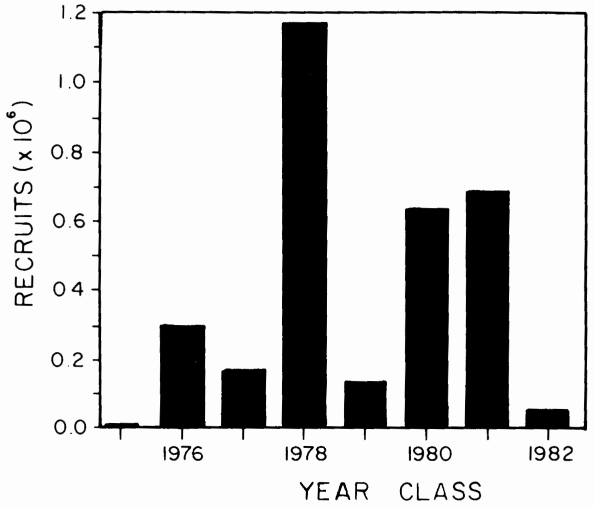

FIG. 44. Annual estimated catches of age 1 chub mackerel from 1976 to 1982 shown for each year class (MacCall et al. 1985). The strong 1978 year class was produced from a very small population of adults.

TABLE 2. Age estimates from trawl catches of lingcod.

Age (yr)	Number of fish 1982	1983
3	5	2
4	27	47
5	42	152
6	47	148
7	35	74
8	14	30
9	3	12
10	6	7
11	1	4
12	1	6
13		3
14		3
15		—
16		1

estimates of age composition. Catch can be used, however, to identify changes in population size. Most lingcod in the commercial catch are age 5 and age 6 (Table 2). The 1977 year-class would recruit into the catch in 1982 and 1983, and the total lingcod catch from all areas in Canadian waters in these years was higher than in the previous 11 yr (Fig. 45; Tyler and Fargo 1990). Without adequate estimates of the age composition of the catch, it is difficult to identify the exact year or years when strong year classes were produced. However, it is probable that 1976 was not a strong year class because 1981 was not a year of high catch and it is likely that lingcod would be recruited at age 5. Thus, it is probable that 1977 was a year that produced a strong year class that contributed to the increased catches beginning in 1982.

Northern Anchovy (*Engraulis mordax*)

Northern anchovy are fished off the coasts of the United States and Mexico. The United States fishery started in 1954 with landings of 25 300 t. The Mexican fishery started in 1964. Recruitment to the fishery is considered to occur at a nominal age of 0.5 yr. Before the mid-1970s, the largest combined catch of 141 400 t occurred in 1973. In 1976, the year class was strong and the 1977 year class was the fourth lowest in 31 yr (Methot 1989). In 1978, recruitment was the fourth highest in 31 yr, despite the low spawning biomass. The fishery off the United States coast declined to a very low level in 1983. The fishery off the Mexican coast continued, primarily on age 0 fish. The estimated recruitment time series (Jacobson and Lo 1989) shows the strong year class in 1978 that followed a series of weak year classes (Fig. 46).

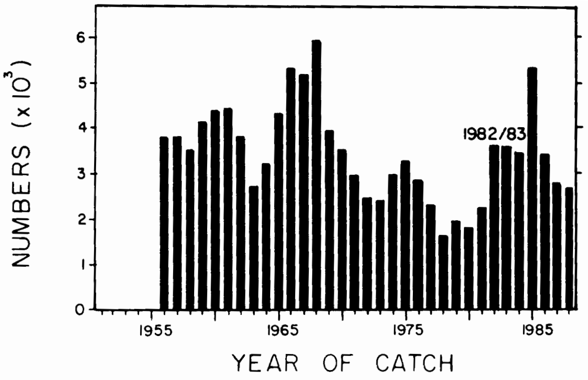

FIG. 45. Canadian catch of lingcod off the west coast of British Columbia, 1956–89.

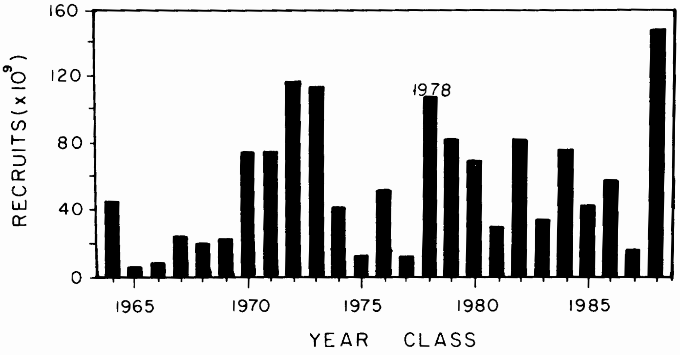

FIG. 46. Estimated abundance of age 0 northern anchovy on July 1 recruited to the fishery from 1966 to 1988 shown for each year class (data estimated from Jacobson and Lo 1989).

Trends in Nonsalmon Recruitment Indices

The data used to identify strong year classes for nonsalmon fishes can be combined using the procedure described by Ebbesmeyer et al. (1991). The year class strength data was converted to a nondimensional anomali index according to the equation

$$[\ln R - (\Sigma \ln R/n)]/\text{Sd}(\ln R)$$

where R is the index of relative year class strength. The relative year class strength indices used were as follows: walleye pollock, 1986 sample collected in the Bering Sea and converted to show relative year class strength (Fig. 32); Pacific herring, the relative abundance of age 2+ herring in the Canadian fishery as estimated by Haist et al. (1988) (Fig. 34); Pacific cod, the number of age 3 fish recruited into the fishery from 1975 to 1985 as estimated by Zenger and Thompson (1989a) (Fig. 36); Pacific ocean perch, the estimated age 9 fish in the Gulf of Alaska population as estimated by Heifetz and Clausen (1992) (Fig. 38); yellowtail rockfish, data used to reconstruct relative year class strengths from a recent unpublished report by R.D. Stanley, Pacific Biological Station, Nanaimo, B.C.; widow rockfish, the number of fish in the catch for each year class in the 1984 fishery as estimated by Lenarz and Hightower (1988) (Fig. 40); Atka mackerel, the number of age 2 fish estimated by Lowe (1992) to be recruited into the fishery from 1972 to 1988; sablefish, the index of relative year class strength developed by McFarlane and Beamish (1992); Pacific hake, the number of age 2 fish estimated by Dorn and Methot (1989) that would be recruited into the fishery from each year class (Fig. 43); chub mackerel, the estimated number of catches of age 1 fish from 1976 to 1984 from MacCall et al. (1985) (Fig. 44); northern anchovy, the estimated abundance of age 0 fish recruited to the fishery from 1966 to 1988 from Jacobson and Lo (1989) (Fig. 46).

The sum of the nondimensional indices (Fig. 47A) shows that from 1962 to 1975, there was a below-average number of strong year classes. The years 1977 and 1978 were years of exceptionally good year class production, with 1977 being the most exceptional in the 27-yr time series. Strong and weak year class production can also be examined by summing the number of species that had positive and negative anomalies for each year (Fig. 47B). From 1960 to 1986 there were at least four species in the data series for each year, from 1964 to 1984 there were at least six species, and from 1971 to 1982 there were between eight and 12 species. In 1977 there were 10 species with positive anomalies (above average year class production) and two species with negative anomalies. In 1978 there were nine with positive anomalies and three with negative anomalies. It is clear from both methods that 1977 and 1978 were years of exceptional fish production in the time series from 1960 to 1986.

It is important to remember that year class strength is rarely known until fish are recruited into a fishery. This period of prerecruitment varies for the species in this report as described. During the prerecruitment period, there must have been adequate food for growth and survival of the strong year classes produced from 1976 to 1978. This indicates that the carrying capacity of the ocean must have changed for the species that produced strong year classes, to be able to support them through the period of prerecruitment.

Discussion

In this report, I provided a relatively long list of examples of fisheries that were affected by the climate events in 1976 and 1977. Each example is quite short and omits detail and references about the biology and stock dynamics because the list of examples makes the paper rather long as it stands. The length of the list, however, indicates the magnitude of the impact the climate events in 1976 and 1977 had on fish production along the west coast of Canada and the United States. In another report (McFarlane and Beamish 1992), we examine the mechanisms responsible for strong year class production of one species, sablefish, and note the importance of the relationships among the intensity of the Aleutian Low pressure system, cooling in the central North Pacific Ocean, and calanoid copepod production.

The evidence in this paper strongly indicates that the period 1976–78, and 1977 in particular, was a time of exceptional productivity for fishes found off the Pacific coast of Canada and the United States. It appears that many species of fish in the Bering Sea and the more northern areas of the North Pacific Ocean had exceptionally strong year classes. However, there is evidence that some species that occur more to the south, particularly those off the coast of California, had improved survival also. The mechanisms responsible for the coast-wide effect on fish populations are poorly understood, but enough is known about the interrelations among climate and physical oceanography to speculate on the reasons for the production of the strong year classes that occurred for 1976–78.

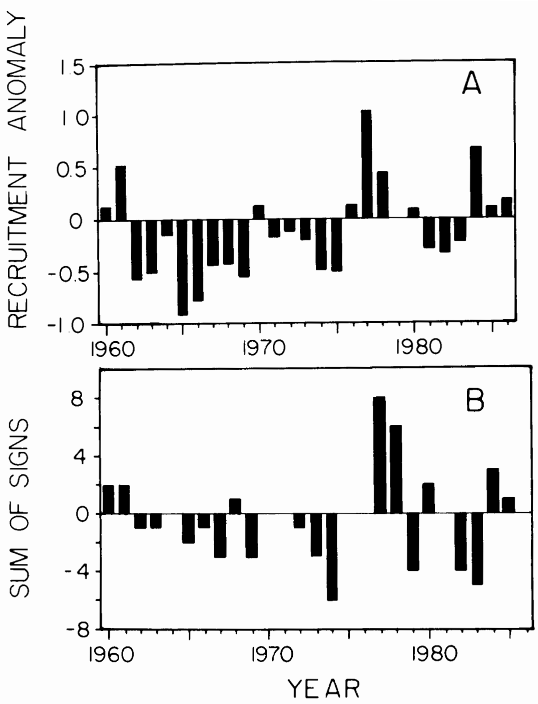

FIG. 47. (A) Anomalies of the sum of the nondimensional indices of recruitment strength of 12 nonsalmon species in this paper showing strong year class production in 1961, 1977, 1978, and 1984 and exceptional production in 1977 and (B) sum of the signs of the positive and negative anomalies showing that in 1977 and 1978, most of the species examined had stronger than average year class survival.

The upper ocean heat storage (or the volume of surface layer water above the thermocline) is closely related to the magnitude of primary productivity (Chavez and Barber 1985; Lewis et al. 1988). The depth of the surface layer regulates productivity because ocean water below the thermocline is approximately 1000 times richer in nutrients than water above the thermocline (Redfield 1958). Climate-induced changes in heat storage affect the depth of the surface layer and are the principal mechanisms regulating primary and secondary productivity (Barber and Chavez 1983; Venrick et al. 1987). Heat loss from the surface waters and increased wind stress will increase vertical mixing, bringing nutrients into the euphotic zone. Reid (1962) proposed that horizontal divergence in the upper layer in the center of the Alaskan gyre brings nutrients into the mixed layer, and Thomson (1981) showed that the horizontal divergence transports this water towards the edge of the gyre. Thus, large productivity changes may result from changes in the depth of the euphotic zone. Beamish and Bouillon (1993) showed that there was a close association between an index of the Aleutian Low pressure system and the all-nation production of Pacific salmon. The smoothed trend of the index they developed changes shape in

1976, indicating a change towards more intense (low pressure) lows in the winter and spring. The intensification of the Aleutian Low beginning in 1976 would increase wind stress and upwelling offshore during the winter of 1976–77, resulting in increased nutrient supply to the surface that could be transported as nutrients, food, or both into rearing areas for young fishes.

The Southern Oscillation Index (SOI) is the difference between the normalized surface air pressure measured at Tahiti and Darwin (Trenberth 1984). El Niño – Southern Oscillation (ENSO) events are characterized by a relatively large positive anomaly followed by a relatively large negative anomaly. Extreme negative anomalies are described as El Niño events and are characterized by low pressures and wet, warm weather in the Northeast Pacific (van Loon and Madden 1981; Emery and Hamilton 1985) resulting in a warming of the surface temperature adjacent to the west coast of North America.

There is an atmospheric link between the intensity of an Aleutian Low and the SOI (Blackmon et al. 1983; Namias 1985). Modelling studies have demonstrated this link through a correlation between sea surface temperatures in the tropics and the North Pacific circulation. Variability in climate and ocean conditions in the Bering Sea is related to ENSO events, and the mechanism for the connection appears to be the Aleutian Low (Niebauer 1988). Nitta and Yamada (1989) and Trenberth (1990) showed that major atmospheric changes occurred in 1976 which persisted for at least a decade (Trenberth 1990). K.E. Trenberth and J.W. Hurrell (unpublished data) used an index of the Aleutian Low pressure system to demonstrate a strong relationship between atmosphere–ocean events in the North Pacific and the tropical Pacific where there was evidence of changes that were precursors for events in the North Pacific. The events in the tropics are associated with changes in higher latitudes through a process called teleconnections (Horel and Wallace 1981). Mysak (1986) noted that intensified Aleutian Lows frequently follow ENSO events but the intensity of the Aleutian Low is not necessarily related to the intensity of the ENSO event and not all ENSO events are followed by intense Aleutian Lows. The 1976–77 El Niño event (Bradley et al. 1987), therefore, is linked with the intense Aleutian Low through the atmosphere, and it is this atmosphere linkage that appears to be associated with midocean production changes.

Venrick et al. (1987) identified a significant increasing trend in total chlorophyll *a* in the central North Pacific Ocean. Chlorophyll *a* almost doubled from 1968 to 1985 and concentrations since 1980 were significantly higher than those before 1974. They detected increases after 1968 but were not able to determine if the increase was continuous or if a rapid change had occurred after 1980. According to their fig. 1, they had only one observation in 1978 and none in 1979, so it was not possible to determine if abrupt changes occurred before 1980. They believed the increases in productivity resulted from large-scale surface cooling combined with increased wind stress. They showed that the average sea level pressure in the winter months north of 25°N was lower from 1980 to 1985 than from 1968 to 1973. This extensive area of low pressure indicated to them that the increase in chlorophyll *a* occurred throughout the North Pacific.

As mentioned, copepod production at Ocean Station "P" (50°N, 145°W, Fulton 1983) was significantly related to the Aleutian Low Pressure Index (McFarlane and Beamish 1992; Beamish and Bouillon 1993). It is known that there was a major increase in zooplankton in the central subarctic Pacific in the 1980s (Brodeur and Ware 1992), suggesting that the abundance of copepods measured at Ocean Station "P" was indicative of a large-scale increase beginning in 1976. Calanoid copepods constitute most of the zooplankton biomass in the epipelagic zone of the subarctic Pacific (Miller et al. 1984). Two species, *Neocalanus plumchrus* and *N. cristatus*, make up most of the copepod biomass (Miller et al. 1984). They are in greatest abundance at the surface from April to July. After this period, they move into deep water where they spawn during winter. The reproductive cycle of this abundant plankton coincides with the reproductive cycle of many fishes, and it is not surprising, therefore, that larval copepods are a major source of food for larval and juvenile fishes.

How the strong production of copepods occurred is less clear. The strong copepod year class could result from an abundance of suitable food for larval copepods, or copepod fecundity might have improved as a result of environmental conditions. However, copepod abundance in one year did not correlate well with copepod abundance in the next year, suggesting that improved copepod production occurs because of improved larval copepod survival. Therefore, the climate and resulting ocean conditions probably served to improve both larval copepod survival and to concentrate copepods along the North American coast.

Climate changes in the North Pacific Ocean can affect the strength of the California Current from the north (Wickett 1967; Bernal 1980; Bernal and McGowan 1981) and from the south as a result of El Niño events (Namias 1985). Because fluctuations in the strength and nutrient content of the California Current affect zooplankton volume off the coast of California more than does coastal upwelling (Chelton et al. 1982), a strong California Current that occurs when the Aleutian Low is intense could produce increases in plankton and these increases are believed to persist for 1–3 yr (Chelton 1981). The El Niño event of 1976–77 could influence the productivity of fish stocks through changes in upwelling along the coast of California (Namais 1985) and by affecting the major winter climate system in the North Pacific. A major change in climate can, therefore, affect productivity of waters from California to the Bering Sea. Hollowed (1990) recently concluded that there was a general relationship between the occurrence of strong year classes and ocean conditions, suggesting that there was a link with large-scale ocean circulation patterns.

The response of fish populations from 1976 to 1978 clearly shows that the environment affects recruitment and cannot be ignored when studying the dynamics of fish populations. The large increases in abundance that occurred for some species from small spawning stocks indicated that stock-recruitment relationships for these and probably other species discussed in this paper can be closely related to changes in the environment. The changes in abundance were large and abrupt and had obvious impacts on the management of fisheries, yet it was a number of years before it was known that such a large and sudden change occurred. The abundance changes clearly demonstrate that physical changes in the ocean can affect the population dynamics of fishes with very different life histories, almost simultaneously, over a vast area. A coastwide, synchronous increase in year class strength of a number of species is a welcome event for fishermen and fisheries managers. However, it is to be expected that there will be periods when environmental conditions result in poor survival and managers need to recognize when these conditions are occurring and make timely adjustments to fishing plans that recognize that the changes in abundance are occurring for natural reasons. It is also to be expected that similar events have occurred in the past and that the explanations for the abundance changes that appear in the literature may need to be revisited.

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