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Synchrony of abundance trends of chinook and coho populations off Oregon, Washington and in the Strait of Georgia in comparison with the trends in all-nation catches of Pacific salmon

by

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Abstract

This paper reviews recent studies that describe the trends in abundance of chinook and coho stocks to show that the abundance fluctuations are related to large scale climate events. The abundance trends of chinook and coho populations off Washington, Oregon and in the Strait of Georgia are also linked with the trends of Pacific salmon populations that occur farther north, but the trends are opposite in phase.

The implications of these decadal scale shifts in the mean productivity trends for assessment biologists are that the shifts occur quickly and that these natural impacts must be separated from a data series before the effects of fishing and habitat degradation can be studied. The implications for managers are that good management may not be equated to producing more fish and that management should be more precautionary during regimes that reduce carrying capacity. Certainly, past and future management strategies should be assessed using this new knowledge that changes in catch trends may be linked to climate-ocean shifts. Projections of the impacts of global warming should also be reassessed to consider how these natural shifts may be affected in addition to the familiar response of fishes to temperature.

Introduction

There is an extensive literature that contains information about the freshwater life history of Pacific salmon. However, Pacific salmon are as much a marine species as they are a freshwater species. In fact, salmon spend most of their life in salt water after they have hidden their eggs in fresh water. If the average days in fresh water are compared to the average days in salt water for all species and the number of days is weighted by the relative abundance of the species, Pacific salmon, in general spend approximately 75% of their post hatching life in salt water.

Some of the recent studies describing shifts in the long-term trends in ocean variability have been linked to trends in salmon abundance. The effects which appear as changes in the long-term mean trend of ocean survival occur quickly and cause large changes in the equilibrium abundance. As these changes in mean productivity were seldom considered in past management strategies, future management of Pacific salmon may have to undergo some fundamental changes. Rothschild (1996) writes that the significance of the discovery of persistent trends in Pacific salmon abundance and decadal scale shifts in the environment, if valid, extends well beyond these specific examples. He concludes that "if the productivity of fisheries follows interannual, decadal, or other long-term climate changes, then changes in catch ... such as the notable decline of certain fisheries in recent years ... need to [be] interpreted in the context of these natural cycles, as do ensuing decisions of the management and allocation of stocks".

In this report, I summarize the recent information relating changes in the abundance of chinook and coho to decadal scale, climate-ocean events. These stocks in the Strait of Georgia and off the west coasts of Washington and Oregon (Fig. 1) were particularly important for the recreational fishery and as the abundance declined, a substantial effort was made to stop the decline and "rebuild" stocks to previous high levels. Despite this extensive effort and expenditures, the stocks have not "rebuilt". The recent information on the impacts of climate-ocean regime shifts on salmon, appears to be the answer to the question of why chinook and coho stocks did not respond as expected.

All-nation trends in Pacific salmon catches

The all-nation salmon catch has been shown to follow persistent, decadal scale trends (Fig. 2) rather than fluctuate randomly as might be expected (Beamish and Bouillon 1991, 1993). The catches are approximately 90% pink, chum, and sockeye and 10% chinook and coho. In recent years, catches declined steadily in the 1960s until the mid-1970s. After the 1976-1977 climate-ocean regime shift which was associated with an intensification of the Aleutian Low, catches increased rapidly, reaching historic high levels by the late 1980s and early 1990s. The increase was particularly dramatic for Alaskan salmon (Hare and Francis 1995).

Evidence from the Strait of Georgia

The Strait of Georgia is connected to the Pacific Ocean in the north by Johnstone Strait and in the south by Juan de Fuca Strait. Approximately 80% of the fresh water entering the Strait of Georgia comes from the Fraser River. Wind mixing is the dominant physical mechanism that entrains nitrates from the nitrate-rich deep water into the surface layer in the Strait of Georgia. Modeled impact of wind events on nitrate fluxes (St. John et al. 1993) in the southern strait, showed that nitrate entrainment in the surface layer was reduced when runoff from the Fraser River was high because greater energy was required to break down the more buoyant surface layer. When Fraser River flows were reduced, wind mixing was more effective and productivity increased. However, Beamish et al. (1995) showed that it was also the change from a high to a low flow and vice versa that affected the survival of chinook and coho.

Vertical temperature profiles were taken 8 - 20 times each month in the deep water at the Nanoose Bay Navel Underwater Weapons Test Range approximately mid-way between the north and sound ends of the Strait of Georgia. The temperature profiles were collected using several different continuous temperature and depth instruments. Data were checked for spikes and unrealistic parameter values and these data were deleted. In addition, the temperature data were compared to data collected once each month using reversing thermometers and the two data sets agreed well. The range of surface temperatures (0.5m - 1m) was 5.5°C to 20.4°C, with an average annual surface temperature from 1970 to 1977 of 10.5°C and from 1978 to 1991 of 11.2°C (Fig. 3). An intervention analysis (Noakes 1986) indicated that the step shift in temperature in 1978 was significant (step intervention = 0.337, S.E. = 0.165, $p<0.05$). Bottom temperatures were taken at approximately 325m and were summarized as mean annual values (Fig. 3). The range of bottom temperatures was 7.2° to 10.0° C and the step-like increase after the 1976-1977 climate event was also significant. It is clear, therefore, that there was a major increase in the temperature of the Strait of Georgia that was coincident with the basin wide climate-ocean changes in the Pacific oceans.

Trends in flows of the Fraser River were examined using a cumulative sum analysis (Murdoch 1979). This analysis is useful for the visual detection of changes in the trends of flows. From the early 1920s to the late 1940s the flows were below average (Fig. 4A, 4B). The pattern of flows changed in 1945 and from 1946 to 1956 flows were average. From 1957 to 1976 flows increased and were above the long-term average. This period ended abruptly in 1977 when a period of reduced flows began. This period of reduced flow has continued since 1977. Moore (1991) used the mean surface air temperatures for the northern hemisphere (Jones et al. 1986) to study Fraser River flow patterns. During the cold period (1963-1972), both maximum and minimum flows were higher than during an earlier warm period (1938-1947). The timing of the minimum flows was about the same for both periods, but the maximum flow occurred earlier in the spring during the warm decade. Moore (1991) identified a relationship between mean annual Fraser River flow and maximum annual snow accumulation indicating that the depth of the snowpack is related to Fraser River flow. Because the decline in the average snow depth in the Fraser River drainage from 1977 to 1988 relative to the 1956 to 1976 period (22%) was similar to the declines in flows (28%) for the same period, Moore (1991) proposed that the climate change beginning in 1977 caused the decrease in snow levels and the declining trend in flows. The flows from the Fraser River into the Strait of Georgia are important because the resulting estuarine circulation (Thomson 1981) brings in the most of the nutrients that ultimately contribute to the productivity. Thus a change in temperature and Fraser River flows would be expected to change the carrying capacities for fishes within the Strait.

Impact of the regime shift on chinook salmon in the Strait of Georgia

Catches of chinook salmon in the Strait of Georgia began to decline in 1979 (Fig. 5). Catches and escapements decreased until the mid-1980s when regulations were established to stop the decline. At almost the exact same time that catches started to decline, there was an abrupt change in the survival of chinook salmon released from hatcheries into the Strait of Georgia (Fig. 5). The average marine survival of these hatchery fish from 1974 to 1977 was 4.8% compared to 0.65% from 1978 to 1990.

The decline in chinook catch and escapement in the Strait of Georgia could have resulted from overfishing or from decreases in the capacity of the strait to support chinook or both. If overfishing was the principal reason for the decline, there would be a gradual reduction in smolt production beginning at the time the declines occurred.

The largest catches and spawning escapements occurred in the late 1970s. Beamish et al. (1995) used the estimated escapements and a cohort analysis to estimate wild smolt production at this time. An average of 34 million wild and 2 million hatchery smolts were estimated to have been produced in the late 1970s.

In recent years, there has been a large increase in the number of chinook produced in hatcheries. Beamish et al. (1995) were able to identify these hatchery-reared chinook using the daily microstructure in the otolith (Zhang et al. 1995). Because the number of hatchery-produced chinook was known, it was possible to estimate wild smolt abundance by determining the percentages of hatchery and wild fish in samples of chinook smolts collected throughout the strait. In 1992, 50% of the smolts were estimated to be from hatcheries. The total releases were 40.8 million, thus there were approximately 40.8 million wild smolts in the strait or a total of 81.6 million. The total number of smolts in 1992, was approximately double the total number in the late 1970s, yet the abundance of adults in 1992 was about 25% of the abundance in the late 1970s. This could only occur if there was an 8 fold decrease in marine survival, which is very close to the decline observed in hatchery survival. Thus, the synchrony of the beginning of the decline in catch and the Pacific wide regime shift, indicates that the two events were probably related. Fishing effects could of course exacerbate the rate of decline, but the failure of the population to respond to the doubling of smolt production is both strong evidence of a marine carrying capacity change, coincident with the 1976-1977 climate ocean change and evidence that overfishing may not be the primary reason for the decline in abundance.

Impact of the regime shift on coho in the Strait of Georgia

In an unpublished report, Beamish et al. (1995) found that the number of coho smolts entering the Strait of Georgia in the 1990s was almost double the number that entered in the mid-1970s, yet there was no change in the average trend of the catch (Fig. 6). This was explained by the almost 50% decline in marine survival. Although there was no decline in average catch, other studies showed that there was about a 50% reduction in wild escapements. Despite the decline in escapement, there was not a corresponding reduction in wild smolt production, indicating that there was a compensating increase in survival in fresh water. It was proposed that after the decrease in marine survival in the late 1970s, the addition of hatchery fish helped to maintain the carrying capacity of coho and thus kept the catches high. However, in the early-to-mid-1980s, the survival of coho became density related and the additions of more hatchery or wild smolts did not increase the number of coho in the combined catch and escapement (Fig. 7).

In the study, smolt production of coho in the Strait of Georgia from the brood years 1974 to 1976 (catch years 1977 to 1979) was compared with smolt production in the early 1990s. The period in the mid-1970s was a time of relatively high catches of coho and a time when hatchery releases were just beginning to increase. The percentage of hatchery and wild coho in the catch was determined by using tagged hatchery fish. At this time the total hatchery contribution was approximately 30%. The wild coho, i.e. 70% of the catch, was converted to smolts using a 13% marine survival rate determined from tagging studies and escapement was estimated using exploitation rates. The average total wild smolt production was estimated to be between 10.9 and 12.2 million smolts depending on the escapement. The total hatchery and wild smolt production, therefore, was between 15.3 and 17.1 million smolts for the 1974 to 1976 brood years.

The estimate of the number of wild smolts produced in the 1990 and 1991 brood years required estimating the number of hatchery smolts released into the Strait of Georgia for these brood years. Canadian production from the Fraser River and Strait of Georgia hatcheries for the 1990 and 1991 brood years was 7.92 million and 7.28 million smolts respectively. The contribution from U.S. hatcheries was determined using estimates of the catch of U.S. hatchery coho in the Canadian catch and from observations on the proportion of Canadian and U.S. tagged hatchery coho smolts in survey catches. The estimates were 3.8 million for the 1990 brood year and 4.5 million for the 1991 brood year.

The abundance of wild smolts was made by sorting catches into hatchery and wild types using the pattern of otolith daily increments (Zhang et al. 1995). Because the number of hatchery fish entering the strait is known, and the number of hatchery and wild fish in each sample is known, it was possible to estimate the number of wild fish entering the strait using ratio estimates of hatchery and wild fish in the survey catches. For the 1990 brood year, the individual ratio estimates of wild fish ranged from 3.9 million to 11.6 million wild smolts, with a mean of 6.5 and SE of 1.1 million smolts. For the 1991 brood year, the estimates range from 2.4 million to 7.8 million smolts, with a mean of 4.5 and

SE of 0.81 million smolts. There was a marked pattern in the individual estimates for each brood year. For both years, the later the sample was taken, the lower the estimate of the number of wild smolts. The individual samples were treated as replicate ratio estimators of the number of wild smolts entering the Strait of Georgia from the 1990 and 1991 brood years. The decline was fit by a linear model that showed an exponential decline in the number over time. Such a pattern is consistent with a process acting continuously over the interval in which all samples from a brood year were taken, such as a constant higher mortality of wild than hatchery smolts. It suggests for both hatchery and wild smolts that the most mortality in numbers occurs in the first days after entering the sea. The observed pattern is not consistent with a differential point event sometime during the sea life of coho. The model estimated the 1990 brood year to consist of 18.5 million smolts (SE=3.2 million) on May 15, 1992, and the 1991 brood year to consist of 12.3 million smolts (SE+1.4) on May 15, 1993. Because these estimates on May 15 are based on extrapolating a logarithmic model near its intercept, changing the date of entering the strait would affect the size of the estimates somewhat. However, the best estimates will always be substantially larger than the largest observed estimate, which were 11.6 and 7.8 million smolts for the 1990 and 1991 brood years, respectively.

The total number of coho smolts entering the Strait of Georgia therefore increased from 15.3 - 17.1 million in the mid-1970s to approximately 24.1-30.2 million in the early 1990s. Over the same period, wild smolt abundance remained relatively unchanged or increased slightly (10.9 - 12.2 million in the mid-1970s and 12.3 - 18.5 million in the early 1990s). At the same time that these increases occurred, there was no trend in the catch in the strait, that averaged approximately 800,000 fish each year from 1970 to the present. The increase in total smolt abundance, without an increase in total returns is an indication that factors in the ocean were responsible for the inability to increase total returns. The timing of the change in marine survivorship coincides with abrupt changes in the temperature of the Strait of Georgia mentioned earlier and to the basin scale climate-ocean changes in the North Pacific

Beamish et al. (1997) identified a recent change in the pattern of the Aleutian Low that began about 1990 (Fig. 8). It is interesting that coho catch and survival changed again about this time resulting in reduced catches and reduced survival and reduced variation in the annual survival.

Evidence from the study of Columbia River chinook salmon

Anderson (1996) examined the decline of Columbia and Snake River chinook salmon production in an attempt to separate the impacts of human activities and natural, environmental impacts. He documented the decline of chinook catches throughout this century (Fig. 9) noting that the stocks are now at extremely low levels with some stocks now considered to be extinct. The reason for the declines from over 10 million adults to less than two million adults is commonly believed to result from a combination of human impacts that include the degradation of freshwater habitat, dams, and overfishing (Ebel et al. 1989; Wissmar et al. 1994). There is no question that these human interventions reduced the abundance of chinook, but the impact of natural shifts in the trends of equilibrium productivity have not been considered.

Anderson (1996) used the Pacific Northwest Index (PNI) developed by Ebbesmeyer and Strickland (1995) as an indication of shifts in the climate-ocean system that could affect the survival of the Columbia River chinook. The PNI is a composite index that incorporates air temperature at a site south of the Strait of Georgia on the San Juan Islands, precipitation at Cedar Lake in the Cascade Mountains, and snowpack depth at a site on Mount Rainier measured on March 15 of each year. For each parameter the average annual values were normalized by subtracting the annual values from the average of all years and dividing this value by the standard deviation of the average. The resulting three values are then averaged. A positive index represents years that tend to be warmer and dryer and a negative index represents years that are colder and wetter. The PNI does not incorporate the direct measurement of the intensity of the Aleutian Low, although the impacts are measured in the parameters that record precipitation. For comparison, I included two indices of the Aleutian Low (Fig. 10) (Beamish et al. 1997; Beamish and Bouillon 1993; Trenberth and Hurrell 1995). It is apparent from Fig. 10 that the PNI and the indices of the Aleutian Low are related, although the indices have different trends in recent years.

There is a distinct synchrony in the smoothed pattern of the PNI and the catch of spring chinook from the Columbia River (Fig. 9). The warm dry periods (positive index) have been associated with poor survival and the recent shift to the positive index occurred in 1976-1977, the same time as the changes noted earlier. Anderson (1996) and Lichatowich and Mobrand (1995) agree that freshwater habitat degradation and overfishing have reduced the abundance of chinook, but the fluctuations in abundance cannot be explained exclusively by these factors. There is a clear climate-ocean signal in the catch data that confounds the explanation the abundance changes. The climate-ocean effect is particularly important because it occurs abruptly and results in a new productivity regime. This means that the natural marine mortality also follows a pattern of fluctuations around a mean that exists for decadal periods then shifts.

Evidence from off the coast of Oregon

Pearcy (1992) in his book on the ocean ecology of North Pacific salmonids reported that hatcheries have released coho into the ocean off Oregon since the turn of the century. In the 1960s, new hatchery practices and increased releases resulted in a large increase in catches. As a consequence even more hatchery reared coho were released into the ocean. Pearcy (1992) reported that in the early 1970s the catches fluctuated despite a constant hatchery production of approximately 30-35 million smolts. Beginning with the releases into the ocean in 1976 (the 1977 catch), there was a dramatic drop in returns (Fig. 11). Hatchery production continued to increase, but the production of adults did not increase. Eventually catches were so low that fishing was stopped completely.

The failure of hatchery production to "rebuild" stocks (Bottom et al. 1986) raised a number of questions about the usefulness of hatcheries and management effectiveness. A more basic question about the relative importance of the freshwater and marine environments in determining abundance surfaced, and remains a provocative question among biologists.

A number of explanations were proposed for the reduced productivity beginning in the late 1970s, including the existence of a shift in the ocean carrying capacity. However, it now appears that the reduced marine survival that occurred synchronously with the 1976-1977 climate-ocean regime change was part of the synchronous response observed for most chinook and coho off the coasts of Washington, Oregon and in the Strait of Georgia. It is rather amazing how similar the responses were off Oregon (Fig. 11) and in the Strait of Georgia (Fig. 5, 7).

Evidence of an inverse relationship with salmon production at the northern end of their distribution

The all-nation catch of all species clearly shows trends in abundance as reported previously by Beamish and Bouillon (1991, 1993). The recent increase occurred at the time of the 1976-1977 climate-ocean regime shift. It is clear from the Strait of Georgia catch data and marine survival measurements that the decrease in trends occurred at approximately the same time as the increase in all-nation production. However, catch data for salmon in the Strait of Georgia are not reliable earlier than about 1970. More reliable data exist for catches of coho off Washington-Oregon-California and Francis and Sibley (1991) have used these data to show the inverse relationship with catches of pink salmon catch in the Gulf of Alaska (Fig. 12). They show quite clearly that the periods of highest and lowest catches are opposite in trends. Francis and Sibley (1991) suggest that the existence of distinct oceanographic domains (Ware and McFarlane 1989; Wickett 1967) may explain why the trends are reversed. A key point made by Frances and Sibley (1991) was that when salmon production is studied over a long time scale, there is good evidence that the decadal scale variability is significantly affected by the marine environment.

Conclusion

It is apparent that there was a synchronous decrease in the marine survival of chinook and coho in the Strait of Georgia and off the coasts of Washington and Oregon that was coincident with the 1976-1977 climate-ocean regime shift. The decrease in survival was opposite to the increase in survival observed for most other stocks of Pacific salmon found farther north. This means that it is probable that the global scale climate shift that occurred in 1976-1977 affected the marine ecosystems in a manner that decreased the carrying capacity for Pacific salmon at the southern end of their range and increased the carrying capacity at the northern end. The Strait of Georgia ecosystem appears to be linked to the changes off Washington and Oregon by means of the estuarine circulation (Thomson 1981) that draws in bottom water from offshore to compensate for the Fraser River water that flows offshore on the surface. Thus, there appears to be some linkages in the ocean that were associated with the synchrony of the response.

The implications of these decadal scale shifts in the mean productivity trends for assessment biologists are that the shifts occur quickly and that these natural impacts must be separated from a data series before the effects of fishing and habitat degradation can be studied. The implications for managers are that good management may not be equated to producing more fish and that management should be more precautionary during regimes that reduce carrying capacity. Certainly, past and future management strategies should be assessed using this new knowledge that changes in catch trends may be linked to climate-ocean shifts. Projections of the impacts of global warming should also be reassessed to consider how these natural shifts may be affected in addition to the familiar response of fishes to temperature.

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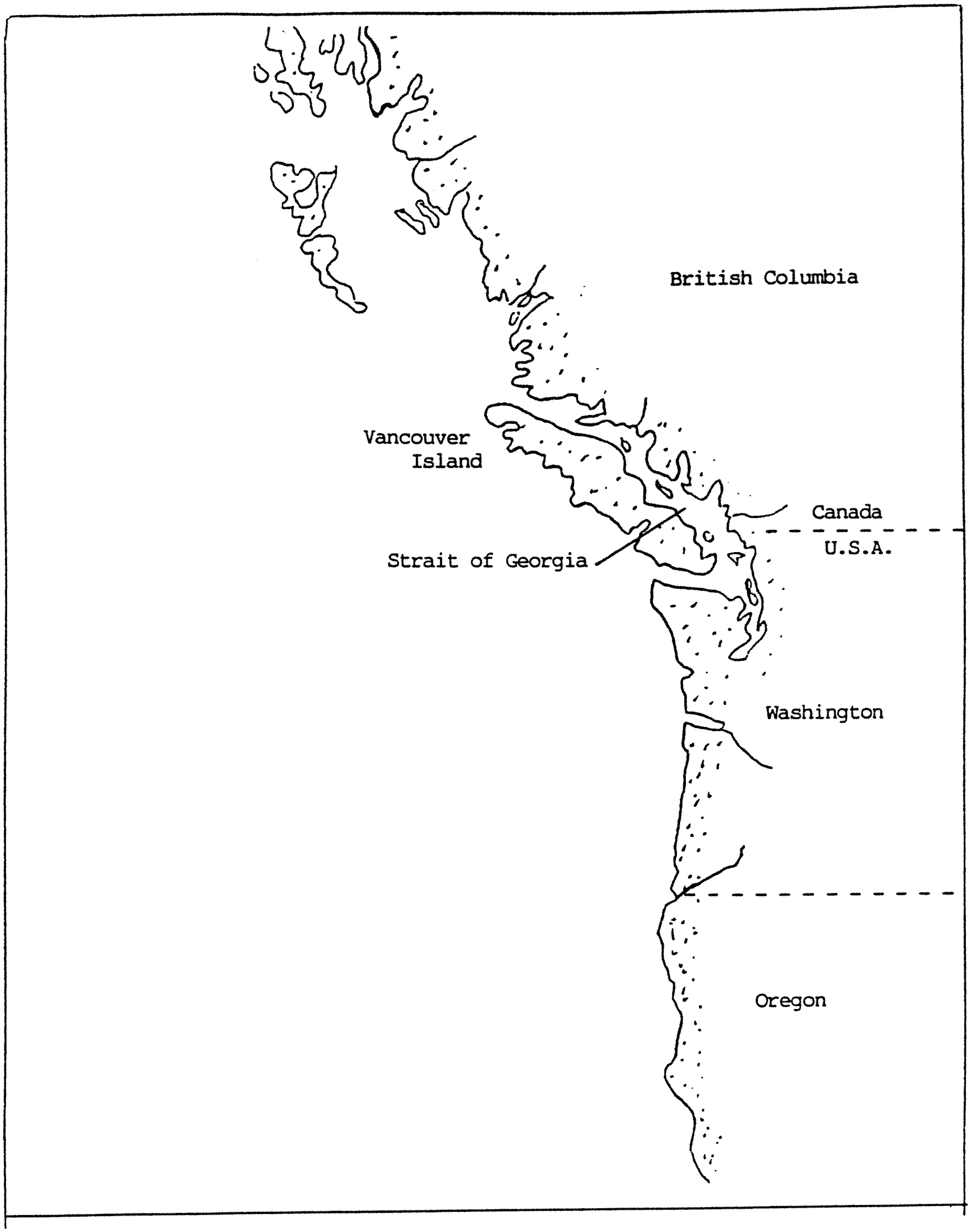

Fig. 1. Pacific Coast of Canada and the United States showing the study areas.

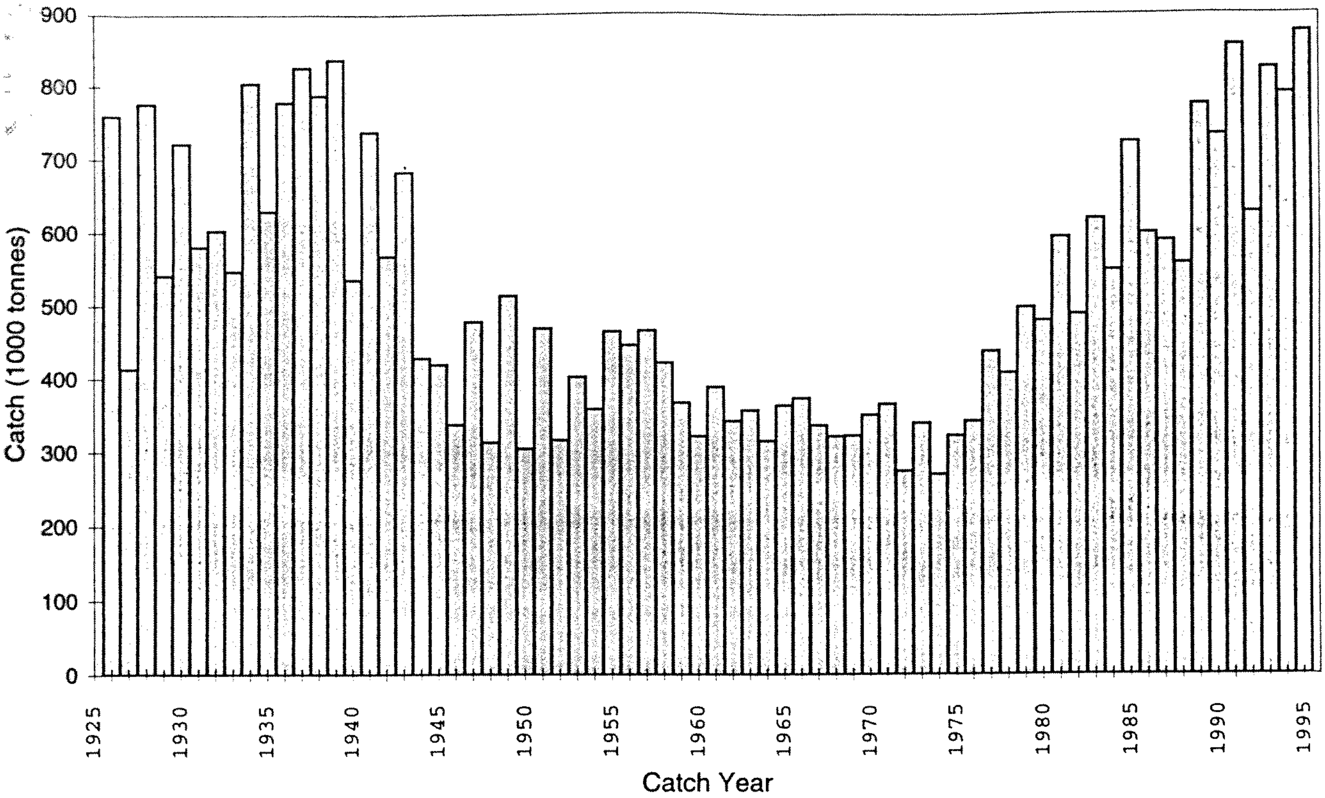

Fig. 2. All-nation catch of Pink, Chum and Sockeye salmon.

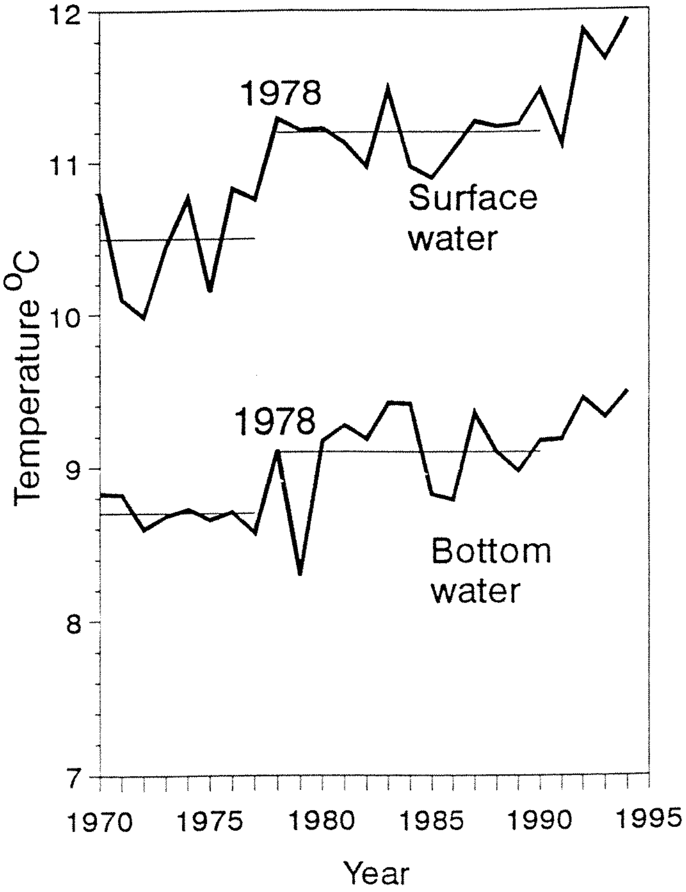

Fig. 3. The trend in mean annual surface and bottom temperatures in the Strait of Georgia, showing the effects of the 1976-1977 regime shift and the possible effects of another change in the early 1990's.

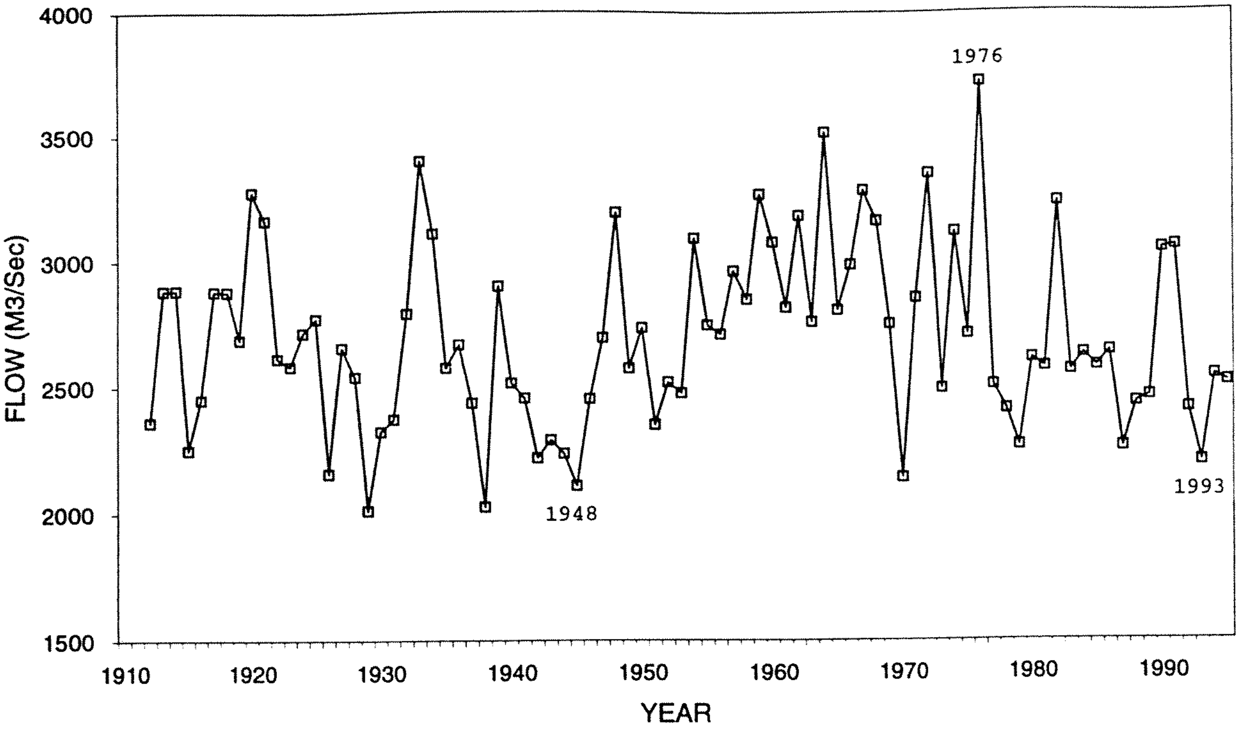

Fig. 4a. Trends in the total annual flow of the Fraser River expressed as m^3/sec.

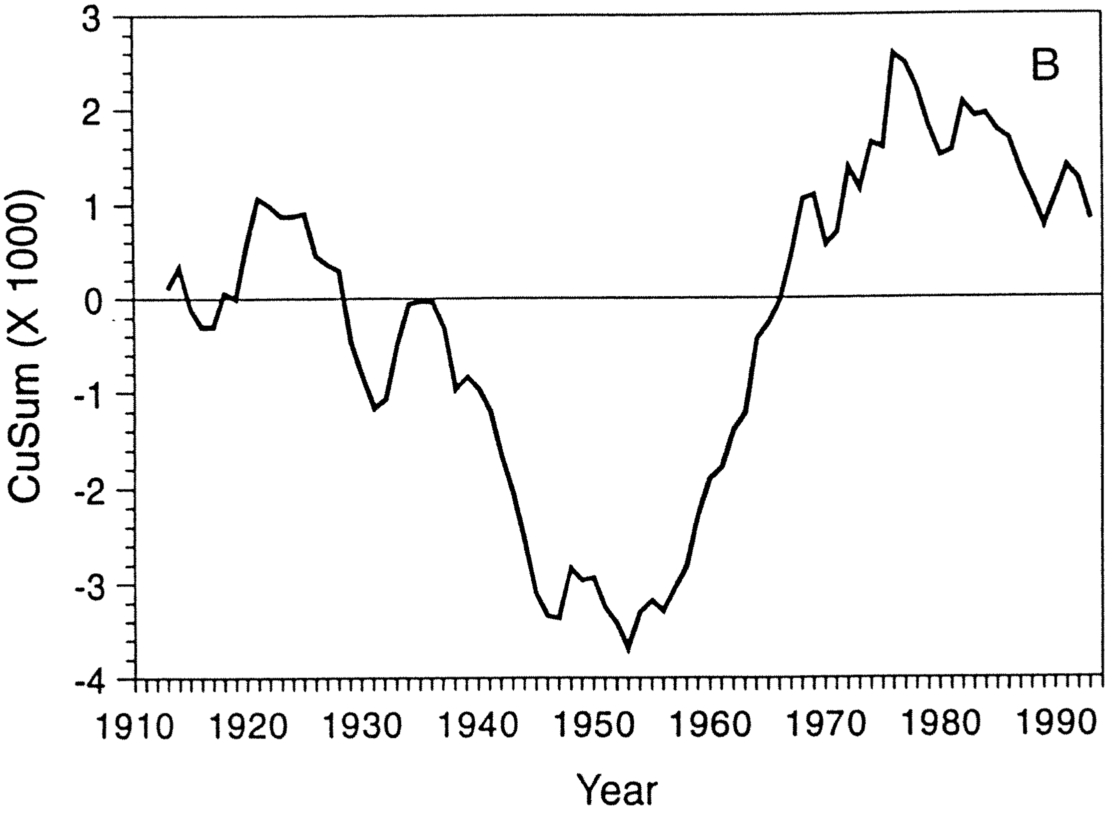

Fig. 4b. The CuSum analysis of the data in Fig. 4a, showing the periods of change. The increasing and decreasing trends represent periods of above and below average flows, respectively. Horizontal trends indicate periods of average flow.

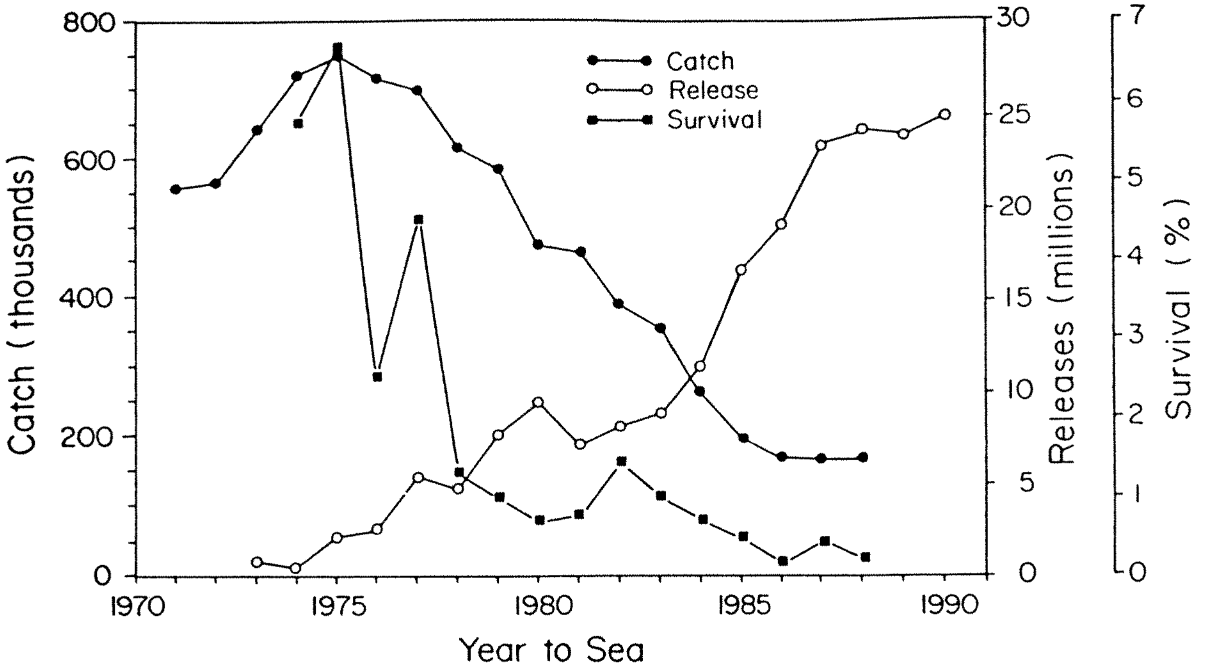

Fig. 5. The decline in chinook catch in the Strait of Georgia, compared to the increased production of hatchery smolts and the decline in the observed marine survival of these smolts (from Beamish et al. 1995).

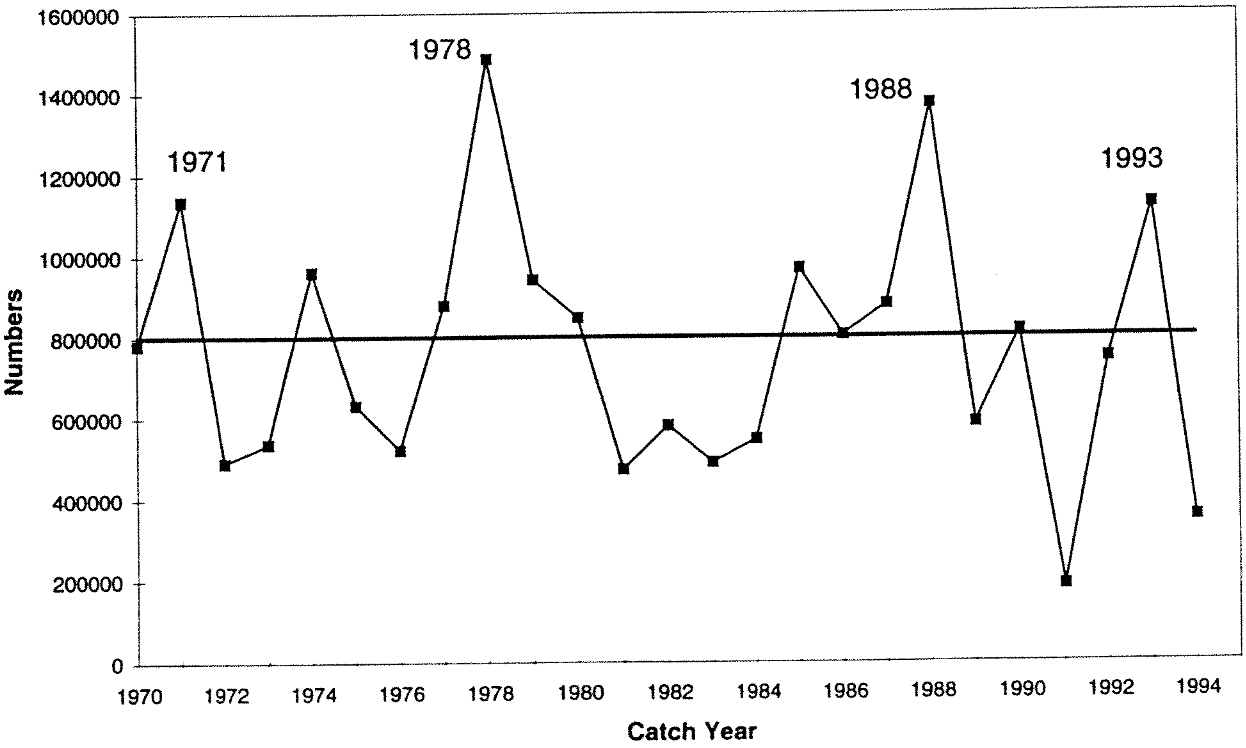

Fig. 6. Catch of coho in the Strait of Georgia by all gear from 1970 to 1994. A catch of 800,000 is shown to illustrate that the trend in catch has not changed substantially. This catch does not represent the total catch of these stocks, only the catch in the Strait of Georgia.

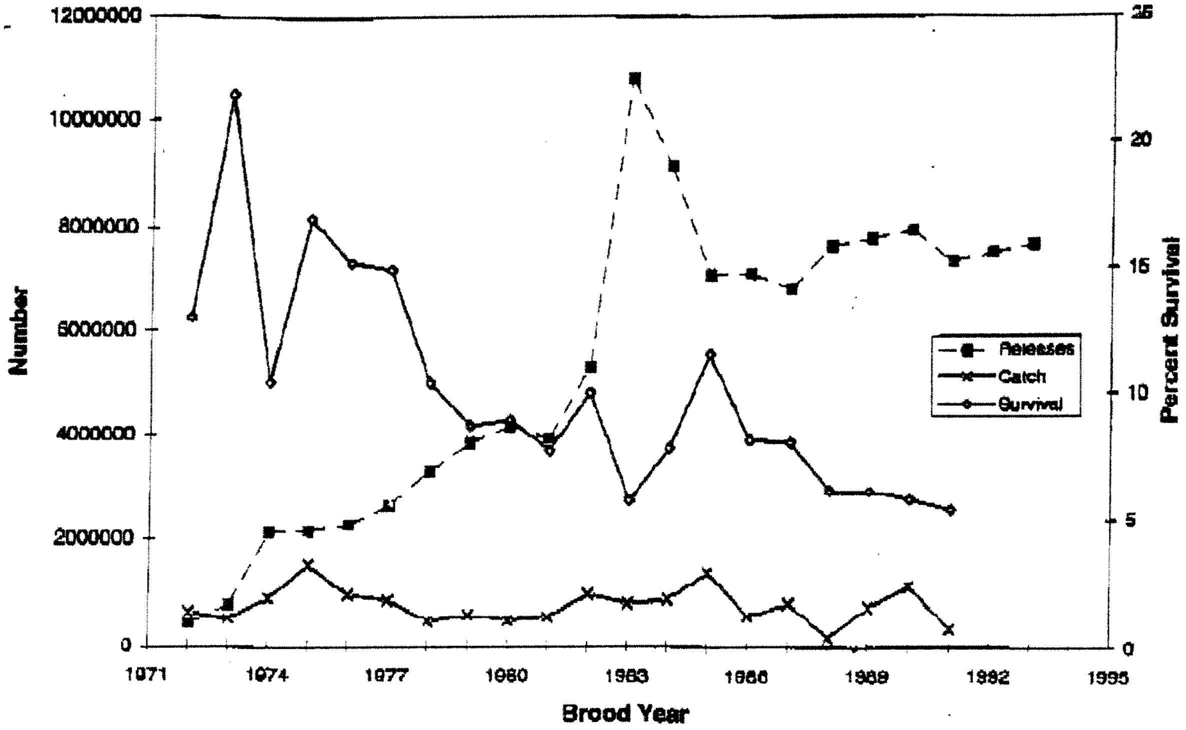

Fig. 7. The catch data from Fig. 6, compared to Canadian hatchery releases of coho and the resulting marine survival. The U.S. hatchery releases are not included; if included, the U.S. data would increase the trend of the releases in the 1980s (see text). Note that the years are brood years (i.e., the catch year would be three years later and the year to sea would be two years earlier).

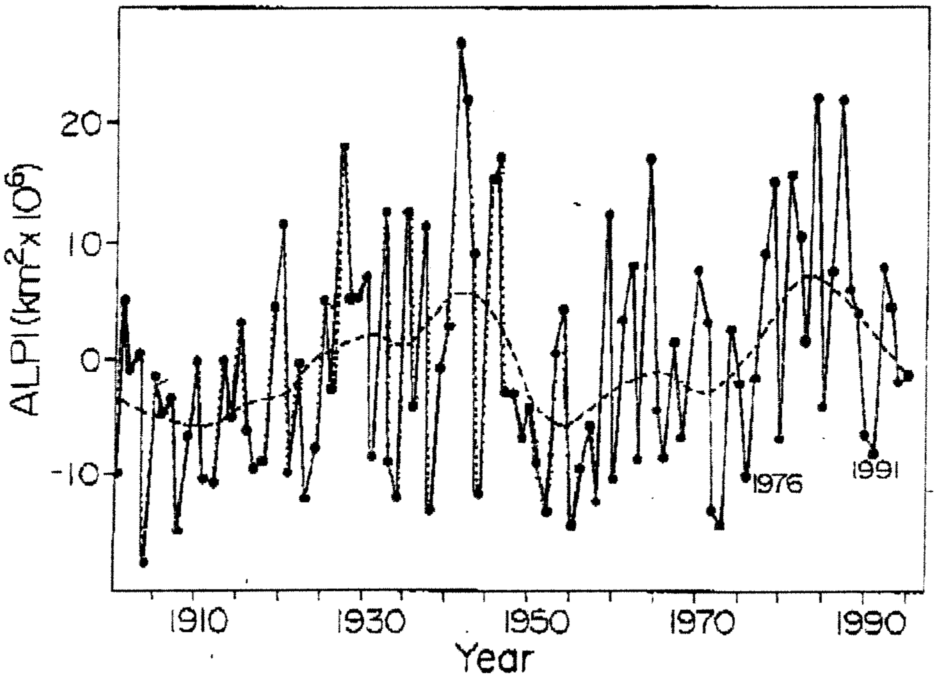

Fig. 8. The Aleutian Low Pressure Index (ALPI) modified from Beamish and Bouillon (1993). The modified index is for December through to the end of March with the year referring to January in the 4-month series. The anomaly for each year is the average monthly value for the 4-month period subtracted from the average monthly value for the time series. The series of intense lows in the 1980s is apparent as is the shift to a pattern of less intense lows in the 1990s. The dashed line is the Loess smoothed line.

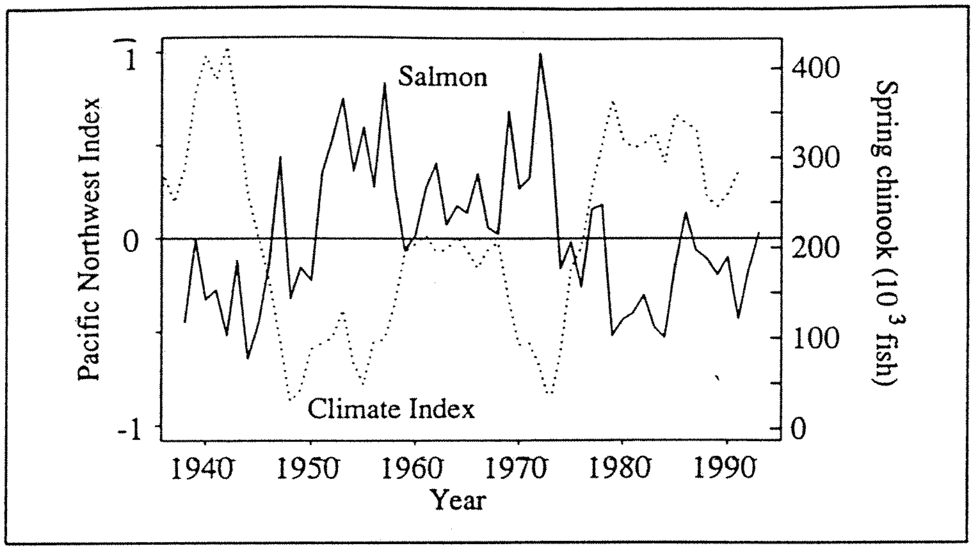

Fig. 9. Anderson's (1996) comparison of spring chinook salmon production in the Columbia River in comparison to the Pacific Northwest Index (PNI). Both data series were smoothed using a running average of 5's.

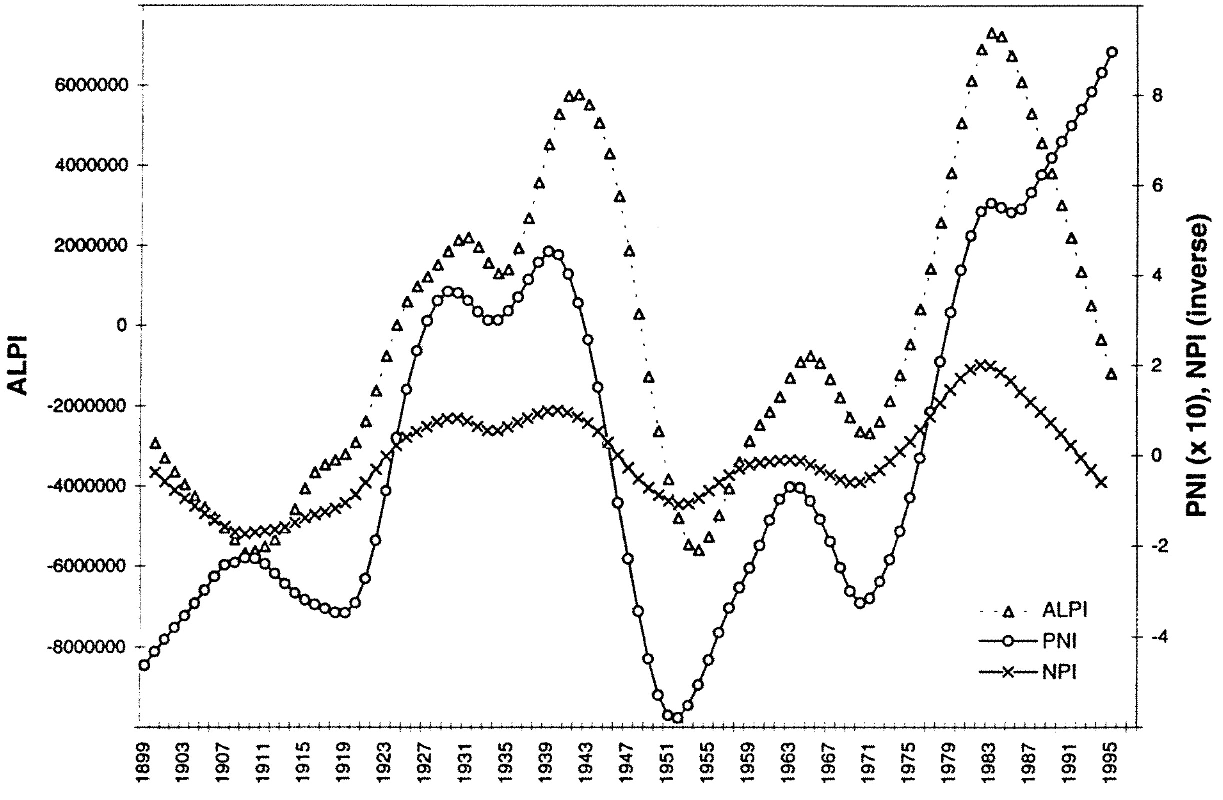

Fig. 10. The loess smoothed periods of the indices of climate over the North Pacific. The ALPI is from Fig. 8, The North Pacific Index (NPI) is from Trenberth and Hurrell (1995) and has the sign of each value reversed to facilitate the comparison with the ALPI (ALPI measures area of intense lows and NPI measures the actual pressure. Thus a very low pressure year will have a higher ALPI and a lower NPI.) The PNI closely follows the trends of the other two indices, except at the beginning and end of the time series.

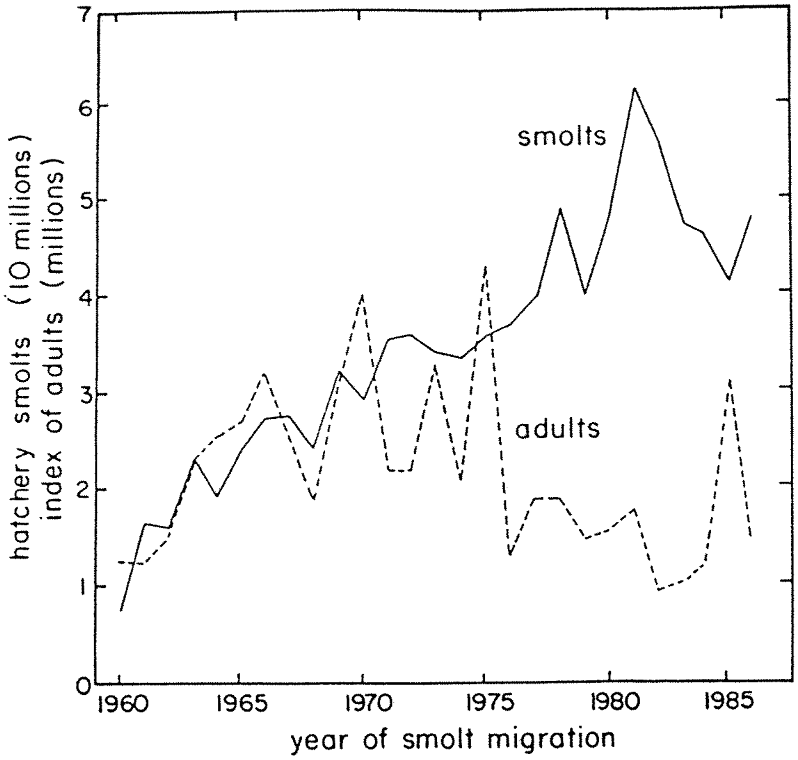

Fig. 11. Pearcy's (1992) figure showing the trends in hatchery production of coho released off the coast of Oregon and an index of adult production. The decline in survival and adult production occurs at about the same time as the changes in the Strait of Georgia.

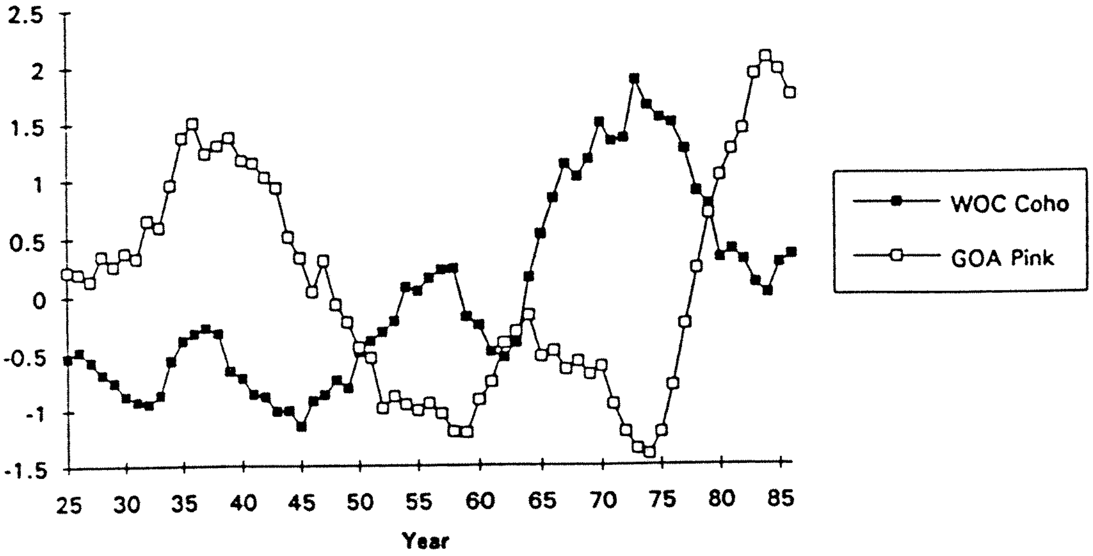

Fig. 12. The trends in the pink salmon catch in the Gulf of Alaska, compared to the coho salmon catch off Washington, Oregon and California. From Francis and Sibley (1991).