Pacific Salmon Production Trends in Relation to Climate

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Pink (*Oncorhynchus gorbuscha*), chum (*O. keta*), and sockeye salmon (*O. nerka*) represent approximately 90% of the commercial catch of Pacific salmon taken each year by Canada, Japan, the United States, and Russia. Annual all-nation catches of the three species and of each species, from 1925 to 1989, exhibited long-term parallel trends. National catches, in most cases, exhibited similar but weaker trends. The strong similarity of the pattern of the all-nation pink, chum, and sockeye salmon catches suggests that common events over a vast area affect the production of salmon in the North Pacific Ocean. The climate over the northern North Pacific Ocean is dominated in the winter and spring by the Aleutian Low pressure system. The long-term pattern of the Aleutian Low pressure system corresponded to the trends in salmon catch, to copepod production, and to other climate indices, indicating that climate and the marine environment may play an important role in salmon production.

Les saumons roses (*Oncorhynchus gorbuscha*), kéta (*O. keta*) et sockeye (*O. nerka*) représentent approximativement 90 % des prises commerciales de saumon du Pacifique faites par le Canada, le Japon, les États-Unis et la Russie. Les prises annuelles combinées de ces pays, de 1925 à 1989, ont montré des tendances parallèles à long terme aussi bien en ce qui a trait aux trois espèces ensemble que pour chacune des espèces prises individuellement. Les prises nationales ont présenté, dans la plupart des cas, des tendances semblables, mais moins prononcées. La grande ressemblance dans le profil des prises combinées de saumons roses, kéta et sockeye pour les quatre pays laisse entendre que des événements communs survenant sur une très grande superficie affectent la production du saumon dans le Pacifique Nord. Le climat dans la partie nord du Pacifique Nord est dominé au cours de l'hiver et du printemps par le système de dépression des Aléoutiennes. L'évolution à long terme du système de dépression des Aléoutiennes correspond aux tendances observées dans les prises de saumons, dans la production de copépodes et dans d'autres indices climatiques, indiquant que le climat et l'environnement marin peuvent jouer un rôle important dans la production de saumons.

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Pink salmon (*Oncorhynchus gorbuscha*), chum salmon (*O. keta*), sockeye salmon (*O. nerka*), coho salmon (*O. kisutch*), and chinook salmon (*O. tshawytscha*) contribute to major commercial fisheries in the North Pacific Ocean and adjacent seas. Approximately 90% of the commercial catch taken each year by Canada, Japan, the United States, and Russia is composed of pink, chum, and sockeye salmon (Table 1). These catches fluctuated throughout this century, with high catches occuring in the late 1930s and 1980s. Changes in the abundance of Pacific salmon are generally considered to be related to changes in the abundance of spawners (Ricker 1954), often referred to as escapement (fish that escape the fishery). As a consequence of Ricker's (1954) studies, management strategies for salmon commonly attempt to maximize sustainable production by achieving optimal spawning escapements. Because a large percentage of salmon returning to spawn are caught in the fishery, the abundance of spawners is generally smaller than catch.

The anadromous life cycle of Pacific salmon makes them vulnerable to overfishing in both the marine and freshwater environments and to degradation of freshwater habitat. Reductions in the quality of freshwater habitat by pollution and reductions in the amount of available habitat throughout this century might be expected to have caused a long-term decline in the survival of salmon eggs and fry. Such a reduction in survival, combined with high exploitation rates, should lead to long-term declines in salmon catch, but the total all-nation catch actually increased beginning in the late 1970s. The dramatic increases in catch that occurred suggested to us that the marine environment was closely linked to the increases in salmon production. However, the survival of salmon in the marine environment is particularly difficult to study and total mortality can exceed 95% (Foerster 1968; Heard 1991; Salo 1991). Much of this mortality is believed to occur shortly after salmon enter salt water, decreasing as the fish grow larger.

The marine distribution of Pacific salmon differs among species (Fig. 1) with overlapping distributions of Asian and North American stocks in the northern North Pacific Ocean. The cli-

TABLE 1. Average catch (1000 t) of Pacific salmon (see text for data source).

	United States	Japan	Russia	Canada	Total
Pink salmon[a]	77.2	68.2	71.1	20.8	237.3
Chum salmon[a]	32.1	69.1	43.0	18.2	162.4
Sockeye salmon[a]	57.3	17.6	8.0	14.0	96.9
Coho salmon[b]	16.5	5.4	4.0	10.7	36.6
Chinook salmon[b]	14.4	0.9	1.5	6.3	23.1
Total	197.5	161.2	127.6	70.0	556.3

[a]From 1926 to 1989.
[b]From 1952 to 1989.

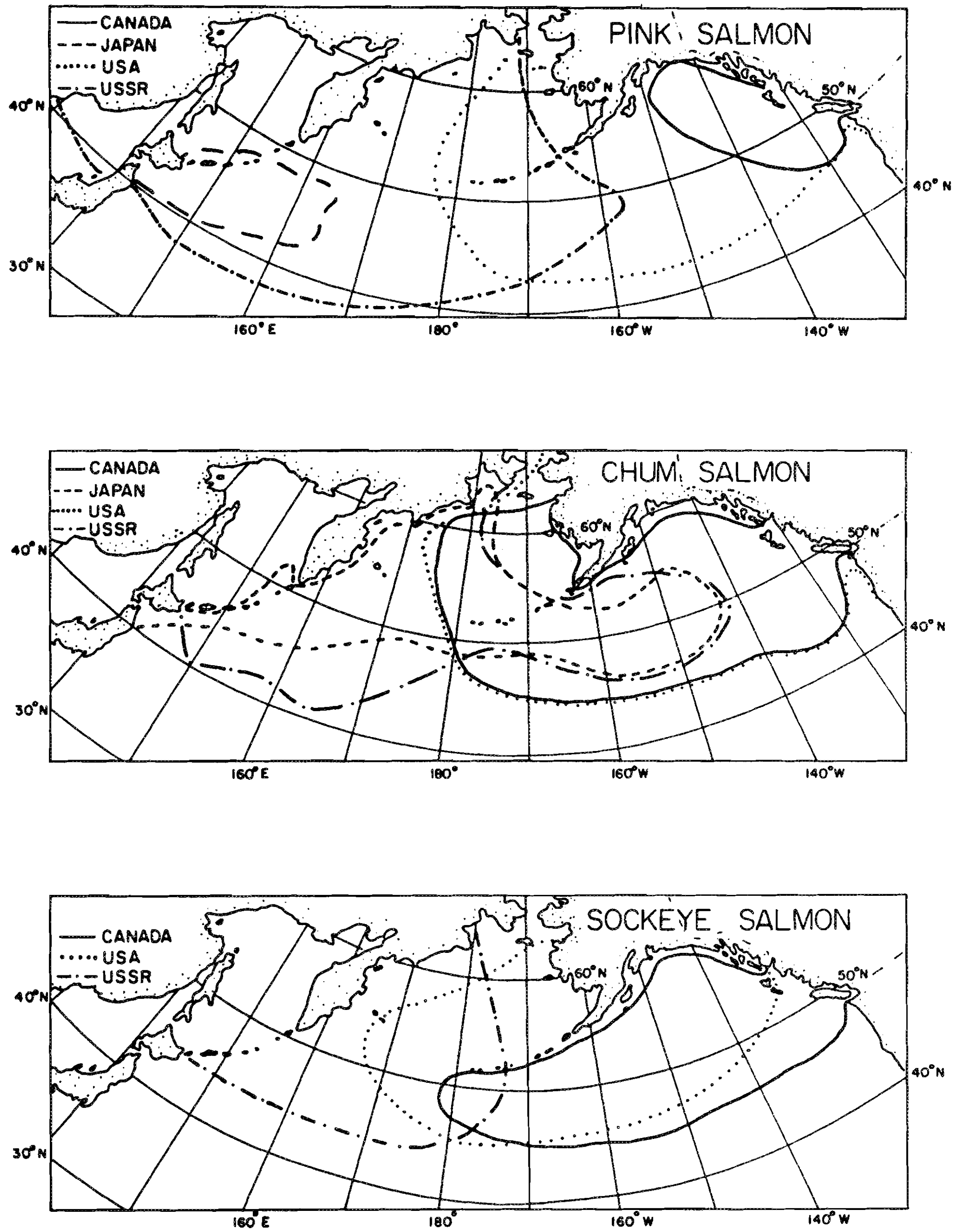

FIG. 1. Known limits of ocean distribution of pink, chum, and sockeye salmon as determined from tag recoveries, 1956–89. Data from Margolis (1990), Neave et al. (1976), and Takagi et al. (1981). Canadian chum salmon distribution includes chum from the Yukon River, Yukon. There are no significant numbers of sockeye that return to Japan.

mate of this region from late in the year to early in the next year is dominated by the Aleutian Low pressure system (Fig. 2). Hence, climate–ocean events in the central northern North Pacific Ocean can affect both Asian and North American salmon stocks and can also influence coastal regions (Royer 1982; Niebauer 1988; Ebbesmeyer et al. 1989). The overlapping distribution of salmon and the potential wide-ranging effects of climate and oceanographic conditions suggest that the changes in production of salmon originating from the four major salmon-producing countries might be affected by common events in the marine environment. Therefore, in this paper, we examine the trends in salmon production in relation to large-scale environmental changes in the northern North Pacific Ocean.

Methods

We did not include coho and chinook salmon in our analysis because catches of these species represent a small proportion of the commercial catch (~10%, Table 1), and in recent years the catches in the recreational fishery have complicated the use of commercial catch as an estimator of salmon production. Commercial catch was used as an index of salmon production for pink, chum, and sockeye salmon. Total returns (catch plus escapement) should be used, but it was not possible to obtain accurate estimates of escapement of all stocks, from all countries, for the time series. Catch is an acceptable index of abundance because a large percentage of salmon stocks is caught in

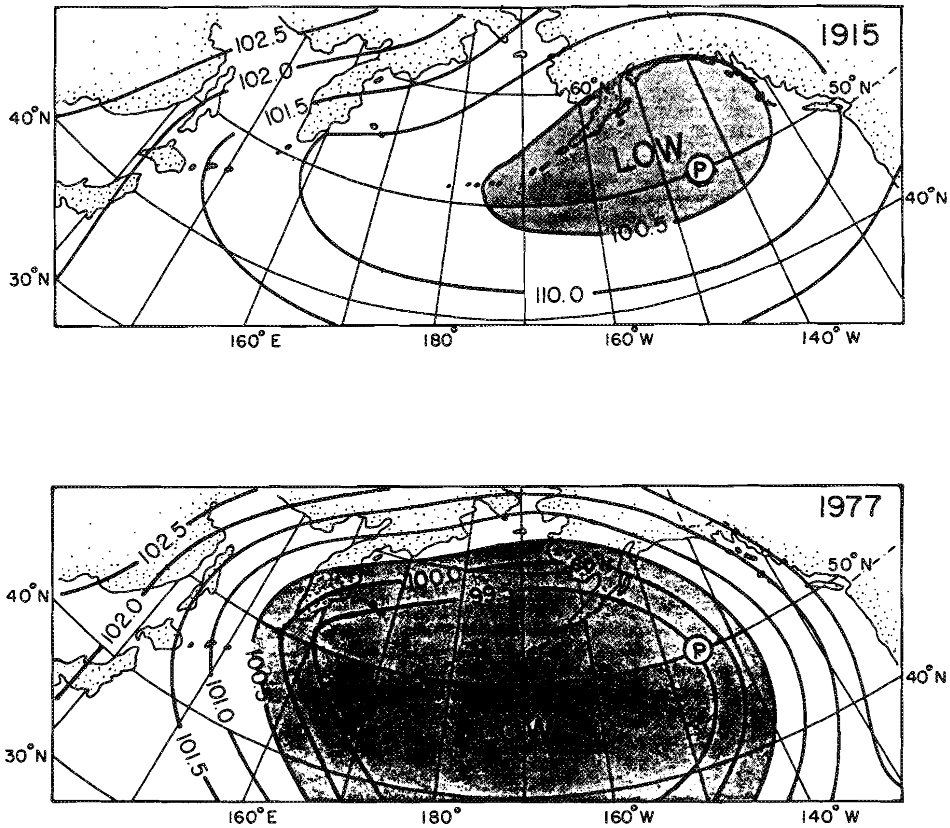

FIG. 2. Examples of a weak Aleutian Low pressure system for January 1915 and a typical intense Aleutian Low for January 1977. Sea surface pressure gradients are in kilopascals. P is the approximate location of Ocean Station P.

the coastal fisheries (exploitation rates typically range from 65 to 85%). We realize that catch may not always be a good indicator of abundance, but for larger aggregates of stocks, we propose that catch trends represent the abundance trends of the total aggregate.

We assembled catch data by country and by species. Our time series started in 1925 because some data sets were missing for years before 1925, and ended in 1989 because data were incomplete after this date. Catches for Canada, Japan, and the United States were coastal catches obtained from the publications of the International North Pacific Fisheries Commission (INPFC) (1977–89, 1979). Russian catches of pink, chum, and sockeye salmon from 1940 to 1974 (Table 2) were obtained from the INPFC (1979). Russian catches from 1925 to 1939 and from 1975 to 1989 (Table 2) were obtained from unpublished catch statistics. Catches of pink salmon in Russia were not available for 1925.

The Japanese high-seas driftnet fishery for salmon intercepted salmon produced in other countries (Shepard et al. 1985). These interceptions affect our analyses when we look at national catch trends and when we examine total salmon production. National trends were difficult to correct, but by combining Japanese and Russian catches into an Asian data base and Canadian and United States catches into a North American data base and then correcting for lost production to the North American data base resulting from the Japanese high-seas salmon driftnet fishery, we were able to compare the production trends of salmon produced in Asia and North America. We used estimates of the number of North American salmon intercepted in the high seas driftnet fishery from 1956 to 1975 from Fredin (1980). Numbers were converted to weight using the annual mean weight of pink, chum, and sockeye salmon caught in the Japanese high-seas driftnet fishery (INPFC 1979). We subtracted this weight from the Asian catch and added it to the North American catch after correcting for lost production using scenario 2 in the method estimating lost production for the all-nation catches that follows.

Calculation of Lost Production due to Japanese High-Seas Driftnet Fishing

Using total North Pacific Ocean coastal salmon catch as an index of total production introduces a bias because lost production resulting from high-seas driftnet fishing is not incorporated in the estimate. Salmon caught in Japanese high-seas mothership and land-based driftnet fisheries are not given the opportunity to put on the substantial growth that typically occurs in the last year of life (Ricker 1976). Before 1952 the Japanese fishery had virtually no impact on the production on North American salmon, but by the mid-1950s there was a well-developed high-seas fishery (Shepard et al. 1985). We estimated potential lost production starting from 1952 for pink, chum, and sockeye salmon and added these values to the known catch. Estimates made previously by Parker (1963), Fredin (1964), and Ricker (1964) used indirect estimates of lost growth (from the time the fish were caught on the high seas to the time they would have been caught in coastal fisheries) based on methods used to convert scale measurements to fish length (Ricker 1976). We estimated lost growth from annual high-seas and coastal mean weight per fish information (INPFC 1977–89, 1979). The mean midpoint of high-seas (mothership and land-

TABLE 2. Russian catches (1000 t) for pink, chum, and sockeye salmon from 1925 to 1989. Data from 1925 to 1939 and from 1976 to 1986: M.Y. Kazarnovsky, VNIRO, Moscow, Russia, personal communication; data from 1940 to 1975: INPFC 1979; data from 1987 to 1989: A.I. Chigirinsky, TINRO, Vladivostok, 690600, Russia, personal communication.

Year	Pink	Chum	Sockeye	Total	Year	Pink	Chum	Sockeye	Total
1925	—	37.9	15.6	—	1958	38.4	27.7	1.0	67.1
1926	138.3	56.9	22.1	217.2	1959	47.1	38.2	4.0	89.3
1927	38.5	56.5	23.4	118.4	1960	19.6	43.3	4.0	66.9
1928	124.0	70.1	38.6	232.7	1961	30.3	36.4	7.8	74.5
1929	26.0	93.0	32.7	151.6	1962	16.3	34.0	4.7	55.0
1930	124.2	105.3	32.9	262.4	1963	35.7	33.6	3.4	72.7
1931	63.7	105.8	25.5	195.0	1964	14.6	25.4	2.7	42.7
1932	142.4	61.4	23.4	227.2	1965	47.9	31.5	4.2	83.6
1933	61.0	73.2	15.2	149.4	1966	20.7	27.6	3.7	52.0
1934	128.8	72.3	3.5	204.6	1967	50.7	20.6	3.0	74.3
1935	43.5	54.3	2.1	99.9	1968	16.3	13.7	2.2	32.2
1936	53.7	74.5	5.3	133.5	1969	63.4	5.9	1.6	70.9
1937	66.2	62.5	7.5	136.3	1970	16.2	12.4	4.5	33.1
1938	72.6	75.8	7.9	156.2	1971	58.4	10.5	2.2	71.1
1939	77.7	66.1	7.3	151.2	1972	20.4	5.1	1.0	26.5
1940	50.4	55.3	3.4	109.1	1973	66.4	5.2	1.7	73.3
1941	77.1	53.7	4.6	135.4	1974	32.3	7.1	1.1	40.5
1942	79.1	39.7	5.7	124.5	1975	69.0	7.8	1.5	78.3
1943	118.1	62.7	7.8	188.6	1976	53.5	15.6	1.1	70.2
1944	106.1	55.5	9.4	171.0	1977	114.4	20.5	1.9	136.7
1945	76.2	61.3	12.0	149.5	1978	55.8	27.2	3.3	86.4
1946	38.3	68.7	13.2	120.2	1979	100.3	19.8	2.8	122.9
1947	132.4	69.3	10.2	211.9	1980	77.4	14.0	3.9	95.2
1948	52.2	62.5	6.2	120.9	1981	86.7	12.4	3.8	102.9
1949	165.0	79.4	8.8	253.2	1982	47.7	11.4	2.3	61.3
1950	36.4	61.5	9.3	107.2	1983	104.3	18.7	4.3	127.3
1951	154.8	83.4	7.7	245.9	1984	54.7	13.7	6.2	74.6
1952	57.9	44.0	9.2	111.1	1985	95.2	20.7	9.6	125.5
1953	142.3	34.0	5.1	181.4	1986	40.8	27.5	8.2	76.5
1954	46.2	52.6	4.0	102.8	1987	101.2	27.3	11.2	139.7
1955	88.3	65.6	3.1	157.0	1988	40.3	26.8	9.3	76.4
1956	72.1	77.3	5.7	155.1	1989	152.7	24.5	10.6	187.8
1957	106.4	32.0	3.5	141.9					

based) catches was assumed to be July 1 of each year (INPFC 1979). The mean midpoint of coastal catches for each species was assumed to be August 1 for pink, September 1 for chum, and August 1 for sockeye salmon (Burgner 1991; Heard 1991; Salo 1991). Pink salmon caught on the high seas typically would have returned to spawn in the year of capture, while some of the chum and sockeye salmon caught in the high-seas fishery would not have spawned for one or several more years (Burgner 1991; Heard 1991; Salo 1991). Because our calculations used estimates of the average weight lost, we needed to estimate the average number of months of natural mortality that pink, chum, and sockeye salmon caught in the high-seas fishery would have experienced had they been able to migrate to the coastal areas. We used three scenarios to determine lost production: scenario 1, chum would experience an average of 2 mo of mortality and sockeye 1 mo; scenario 2, chum would experience an average of 14 mo of mortality and sockeye 13 mo; and scenario 3, chum would experience an average of 26 mo of mortality and sockeye 25 mo. For chum and sockeye salmon, scenarios 1, 2, and 3 refer to fish that all return to the coast either in the current year or the two subsequent years. Because pink salmon are caught in the high seas in the same year they spawn, we estimated an average of 1 mo of marine mortality between capture in the high seas and the coastal fisheries. These scenarios were used to describe the broad range of possible conditions of salmon returning to coastal waters. We assume that scenario 1 will overestimate lost production because of the low marine mortality assumption and that scenario 3 will underestimate production because of the high mortality assumption. Scenario 2, which has chum and sockeye salmon returning the year after high-seas capture, would probably be average conditions. Ricker (1976) concluded that the instantaneous natural mortality rate of sockeye salmon in their final year of life is about 0.015 per month and for pink and chum salmon is about 0.013, with mortality being higher in earlier years. We therefore calculated salmon production losses using a conservative value of M (monthly) = 0.02.

To calculate the potential numbers of salmon that would return to the coast in the absence of high-seas driftnet fishing, we applied the following formula to land-based and mothership high-seas driftnet catches for each species of salmon: $N_t = N \cdot e^{-(M \cdot t)}$ where N_t = total potential catch (in number) of coastal samon in the absence of high-seas fisheries, N = number of salmon caught in high-seas fisheries, M = monthly instantaneous natural mortality rate = 0.02, and t = number of months between catch of fish in the high-seas fisheries and anticipated catch in coastal fisheries as described in scenarios 1, 2, and 3. The total potential catch (N_t) was converted to biomass using the coastal mean weight estimates.

In addition to natural and fishing mortality, Ricker (1976) used noncatch mortality in his calculations of potential lost salmon production. Noncatch mortality includes those fish injured in nets, or preyed upon while caught in nets, that subsequently die as a direct result of their net encounter. We do not incorporate noncatch mortality in our estimates of lost production because of the high level of subjectivity of such estimates. Nevertheless, noncatch mortality would result in higher levels of lost production than those we report here.

Aleutian Low Pressure Index

The Aleutian Low is usually centered over the Aleutian Islands and typically begins forming during the autumn months, intensifies during the winter months, and then breaks down by early summer. A weak or less intense winter pressure system is typical of the pattern observed in 1915, while the system present in 1977 is an example of an intense low (Fig. 2).

We produced mean seasonal sea level pressure maps for the North Pacific Ocean between 20 and 70°N latitude and between 120°E and 120°W longitude using sea level pressure data from the National Centre for Atmospheric Research, Boulder, CO, USA. Hamilton (1984) produced similar maps for the period 1939–82. For the winter (December, January, February) and the spring (March, April, May) of 1899–1990, we calculated the area (square kilometres) of the North Pacific Ocean covered by the Aleutian Low pressure system less than 100.5 kPa. This was accomplished by using a software package called COMPUGRD which produces two-dimensional maps of the region under investigation and calculates the area covered by chosen isobars. We used the sum of the winter and spring Aleutian Low values as an index of historical weather over the North Pacific Ocean to compare with salmon production trends. The Aleutian Low pressure indices were smoothed using a LOWESS smoother (Cleveland 1985) with a common band width, f, of 0.20.

The Southern Oscillation Index or El Niño events are frequently used as indices of climate change. The difference between the anomalies in sea level pressure at Tahiti minus the anomalies at Darwin is the Southern Oscillation Index and the extremes of the index are associated with El Niño (extreme negative anomaly) and La Niña (extreme positive anomaly) events. Instead of using these indices to compare climate events in the South and North Pacific oceans, we calculated the annual mean Darwin atmospheric sea level pressure for December–May. Mean monthly atmospheric sea level pressure at Darwin from 1900 to 1989 was obtained from the Climate Analysis Centre, World Weather Building, Washington, DC, USA.

Because temperature can affect fish production directly and indirectly, and because temperature is often used as an index of climate change, we wanted to compare salmon production trends with sea surface temperature trends in the northern North Pacific Ocean. In the absence of a time series of averaged sea surface temperature data for the northern North Pacific Ocean that corresponds to our time series for salmon production, we used the Northern Hemisphere mean surface temperature change developed by Hansen and Lebedeff (1987) as an index of sea surface temperature trends in the North Pacific Ocean. These land temperature data of Hansen and Lebedeff (1987) and Jones et al. (1986) show trends similar to the globally averaged sea temperature record (Reid 1987; Friis-Christensen and Lassen 1991).

We chose two methods to examine salmon production trends. First, we fit a LOWESS smoother (Cleveland 1985) to the catch data using a common band width, f, of 0.20. We also analyzed the data using a cumulative sum analysis, which plots the cumulative sum of the residuals around a mean value (Murdoch 1979; Campbell et al. 1991). This method provides a visual pattern of trends in the time series because changes in the slope are directly related to changes in the mean up to that point. Cumulative sum plots clearly identify inflection points in trends, and the position of the inflection points cannot be adjusted by manipulating the analysis as can be done by some other smoothing methods.

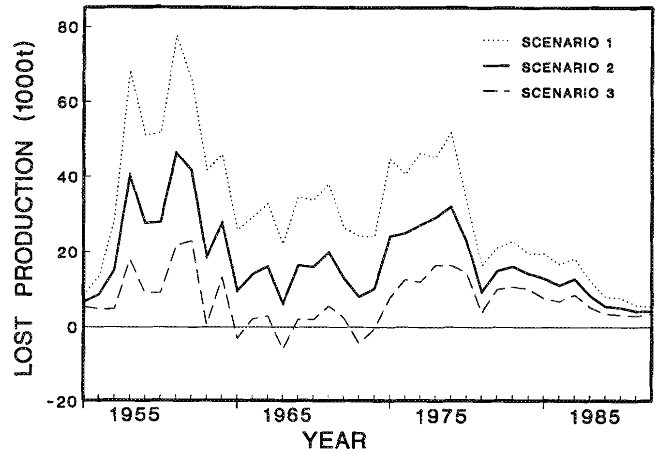

FIG. 3. Potential lost production of pink, chum, and sockeye salmon resulting from Japanese high-seas mothership and land-based driftnet fishing. Lost production varies depending on the mortality schedule chosen for each species, as depicted by scenarios 1, 2, and 3 (description in text).

Marine Survival Trends

We selected marine survival data for Japanese chum hatcheries to compare with the Aleutian Low Pressure Index because the hatchery data were available, the quality was good, and the total fishery represents a large percentage of the recent all-nation salmon catch. Data for Japanese chum hatcheries were from (M. Kaeriyama[1]). The Japanese data do not include estimates of lost production resulting from high-seas interceptions.

Results

Estimates of Lost Salmon Production Resulting from the Japanese High-Seas Salmon Driftnet Fishery

The range of estimates of lost salmon production, calculated using the three scenarios of salmon mortality, was greatest from the mid-1950s to the mid-1970s, coinciding with the peak of the high-seas fishery (Fig. 3). As high-seas fishing effort declined into the 1980s, the estimates of lost production decreased. Scenarios 1 and 3 represent the possible extreme estimates of lost production and were not used to adjust catches. Because scenario 2 represented an average amount of mortality, it was used to estimate lost production. In scenario 2, lost production ranged from approximately 4000 to 45 000 t over the time series. Lost production peaked in the 1950s at about 45 000 t, declined in the 1960s to an average of almost 15 000 t, increased to almost 25 000 t in the early 1970s, and then declined abruptly from 1976 to about 10 000 t in 1978 and gradually declined to about 4000 t by 1989 (Fig. 3).

[1]Paper presented at the International Symposium on Biological Interactions of Enhanced and Wild Salmonids, June 1991, Nanaimo, B.C. (unpublished).

Ricker (1976) reported that gains from eliminating Japanese high-seas fishing would be 76% of the weight of fish caught in the high-seas fishery for North American sockeye and 86% for Asian sockeye. Our estimates of lost production are smaller than previous estimates (Ricker 1964), mainly because we did not incorporate noncatch mortality (or "dropout") into our calculations. Other differences resulted because Ricker (1964) based growth data on back-calculations using interannuli distance on scales whereas we use mean weight per fish of high-seas and coastal catches. Ricker's calculations show an overall production loss to coastal catches equivalent to approximately 60% of the high-seas catch for all species combined whereas our calculations show an overall loss of about 6%. We used our estimate of lost production, but if we used the higher estimates, the catch trends would be more similar to the index of climate trends.

Catch Trends

Combined all-nation catches of pink, chum, and sockeye salmon (Fig. 4A) averaged 673 100 t from the mid-1920s to the early 1940s (1926–43). Maximum catches occurred in the late 1930s with an historic high catch of 837 400 t in 1939. A period of low catch occurred from the mid-1940s until the mid-1970s, except for a small increase around the mid-1950s (average from 1944 to 1975 was 374 100 t). The lowest total salmon catch of 275 600 t occurred in 1974. In the most recent years, production increased. The 1985 all-nation catch was 719 641 t, the highest in five decades and 86% of the historic high catch in 1939 (Fig. 4A). When the lost production calculated from scenario 2 (Fig. 4A) was added to the all-nation catches of pink, chum, and sockeye salmon, the increase in the mid-1950s was accentuated, but the trend in catch was basically unchanged.

The patterns of the all-nation catch for each of the three species were also similar (Fig. 4C–4H). All LOWESS trends (Fig. 4A, 4C, 4E, 4G) identify high catches from 1925 to the mid- to late 1930s, a decline to the mid-1970s, and then an increase to the end of the data series in 1989. The trends for chum and sockeye salmon indicate that catches in the mid- to late 1980s were equal to or exceeded historic catches in the time series whereas the trends for pink salmon indicated that the catch in the 1980s had not reached previous levels at the beginning of the time series.

The similarity in trends is even more apparent from the cumulative sum analysis (Fig. 4B, 4D, 4F, 4H). Catches of pink, chum, and sockeye salmon were above the long-term mean from 1925 to about 1942, followed by a trend of catches below the long-term mean until 1977 when the trend changed. At this time, chum and sockeye catches increased relative to the long-term mean, while pink catches remained at the long-term mean. The cumulative sum analysis shows a slight change in trends for pink and chum salmon beginning in 1953 and ending from 1956 to 1958. Small differences in the timing of changes in the trends occurred, but the pattern is amazingly similar considering the different management practices in salmon fisheries in the four countries (Shepard et al. 1985) over such a long time series.

The trends in total catches for individual species for each country (Fig. 5) were similar to the general trend in catches observed for combined all-nation and combined individual species catches, but were not as distinct. Salmon catch trends for the United States (mainly Alaska) for pink, chum, sockeye (Fig. 5), and total all-species catch were virtually identical to the trends for all-nation, all-species catches.

Total Japanese catches were high until the early 1940s but were significantly reduced during World War II and for several years afterward (Fig. 5). Catches recovered by the mid-1950s and they remained relatively stable until the mid-1980s. Catches of chum salmon followed the pattern of total catches, except that catches increased dramatically in the mid-1970s in association with the development of a major hatchery program (Kaeriyama 1989). Because the Japanese high-seas fishery catches some chum salmon produced in Russia and the United States, the reported catch only approximates Japanese chum salmon production. Catches of pink salmon oscillated on a downward trend, beginning in the early 1960s. Declining Japanese catches of pink salmon from the mid-1970s mostly reflect reductions in the high-seas interceptions. Japan does not produce anadromous stocks of sockeye salmon; therefore the catch trends of sockeye are not trends of Japanese production, but trends in the interception fisheries.

Russian salmon catches (Fig. 5) appear to have declined slightly during World War II but returned to previous levels until the mid-1950s. Average catches from 1925 to 1933 and from 1941 to 1955 were about equal. Total catches did not increase in the late 1970s and early 1980s, but increased in the late 1980s. Unpublished catch data for 1991 indicate the total Russian catch could be about 250 000 t, the second highest catch in the history of their Pacific salmon fishery since 1925. Chum and pink salmon catches followed the general pattern of total catches, except there were increases in pink salmon catches in the late 1970s. Sockeye salmon catches increased in the early 1920s, declined by the mid-1930s, and remained at low levels until the mid-1980s when there was some indication that catches were increasing.

Canadian catches (Fig. 5) were the lowest of the four countries and catch trends were more variable. Total catches (Fig. 5) were high from 1925 to the early 1940s, were slightly lower up to the early 1950s, increased briefly to the mid-1950s, and remained relatively stable until the early 1980s. The pattern of pink salmon catches was quite variable, but does show a trend to increased catches in the late 1970s. Average chum salmon catches were relatively stable from 1928 to the mid-1950s when the average catch declined. Average sockeye salmon catches did not change until the mid-1950s when there was a small increase; average catches were lower from the late 1950s until the mid-1960s. Average catches increased from the mid-1960s until the late 1970s and again beginning in the early 1980s.

The problems of interceptions that exist when national catch trends are examined can be minimized by looking at catch trends for Asia and North America after correcting for interceptions. The changes in the reported catches resulting from high-seas salmon interceptions and for lost North American production were small relative to the total catch (Table 3). The LOWESS trends (Fig. 6) show that catches in Asia and North America started to decline almost the same time, but the decline was more rapid in Asia. Only the Asian catches showed the small increase in catch in the 1950s. The increase in catch in the late 1970s was much more abrupt in North America (Fig. 6B) than in Asia (Fig. 6A).

Aleutian Low Pressure Index

The Aleutian Low Pressure Index for the years 1900–89 (Table 4; Fig. 7) indicated that sea level pressure was high (low index represents high pressures or less intense lows) over a vast area of the northern North Pacific Ocean at the turn of the century, but the Aleutian Lows intensified steadily until the late

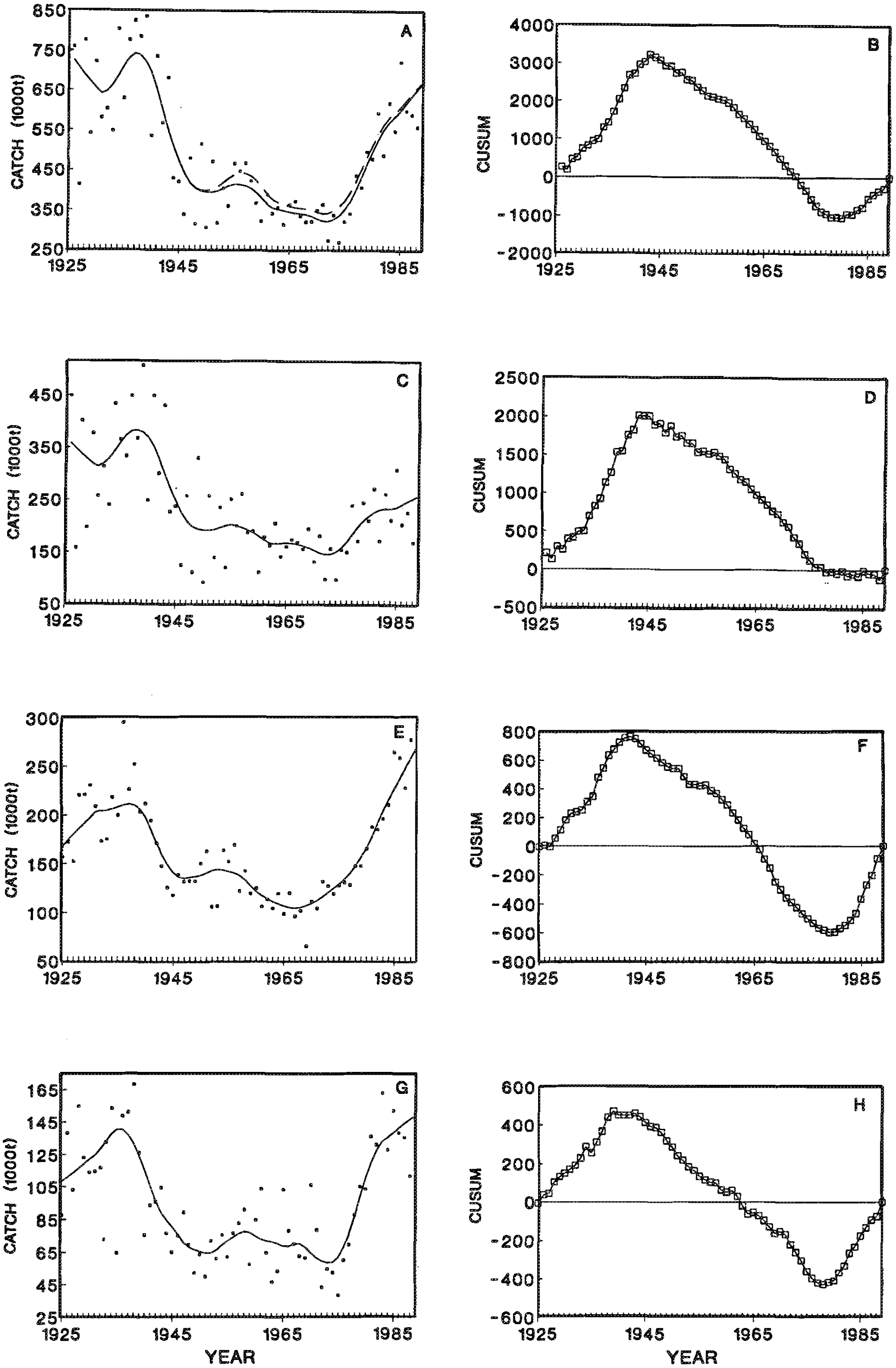

FIG. 4. Trends in catches of (A and B) combined all-nation catches of pink, chum, and sockeye salmon and all-nation catches of each species ((C and D) pink, (E and F) chum, and (G and H) sockeye)). The solid squares in the left-hand panels are the mean annual catches, and the solid line is the LOWESS smoother with a band width, *f*, of 0.20. The open squares in the right-hand panels are the cumulative sum values for the mean annual catches. The broken line in Fig. 4A indicates the potential increase in production if there was no high-seas salmon driftnet fishery. The cumulative sum analysis (Fig. 4B, 4D, 4F, 4H) shows changes in trends of catches relative to the long-term mean (line at 0). "Increasing" trends represent catches that average higher than the long-term mean; "decreasing" trends represent catches that are lower than the long-term mean.

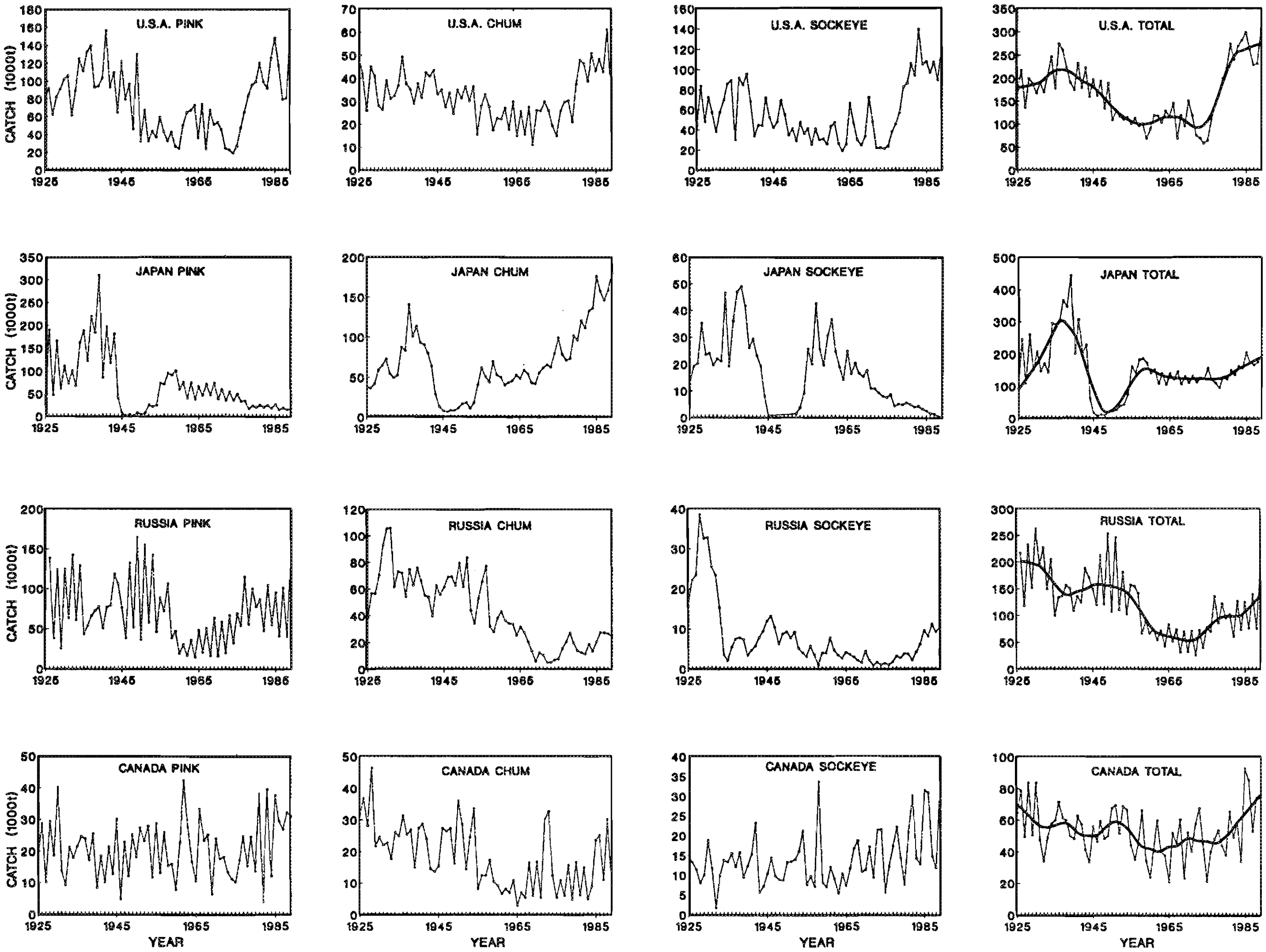

FIG. 5. Catches of pink, chum, and sockeye salmon and the total catch of the three species for United States, Japan, Russia, and Canada. The total catch for each country is fitted with a LOWESS smoother with a band width, *f*, of 0.20.

1930s (high index represents low pressures or intense lows). From about 1940 to 1950 the index dropped, indicating a change to higher pressures. The period from 1950 to 1970 was characterized by high pressure or weak lows except for a small period of intense lows in the late 1950s and early 1960s. Beginning in the early 1970s, the intensity of the lows again increased, reaching the most intense levels in the time series in the 1980s. In the late 1980s, there was a weakening of the Aleutian Low, but it is too early to determine if the trend has changed.

The pattern of the smoothed Aleutian Low Pressure Index (Fig. 7) corresponded closely to the trend in combined all-nation salmon catches. The declines in catches from the late 1930s to the late 1940s correspond to a sharp decline in the Aleutian Low Pressure Index. Similarly, the increases in catches beginning in the mid-1970s followed an increase in the index. There was a small fluctuation in the salmon production index in the early 1950s when the Aleutian Low Pressure Index changed, but catch trends declined again in the late 1950s (Fig. 7). There was no significant correlation observed when we used linear regression analysis to compare the annual Aleutian Low Pressure Index and the annual North Pacific Ocean Salmon Production or when we compared the Aleutian Low Pressure Index with catches lagged 1 yr for pink salmon, 2 yr for sockeye salmon, and 3 yr for chum salmon.

The pattern of the smoothed sea level pressure at Darwin was very similar to the trend in the Aleutian Low Pressure Index after the mid-1920s (Fig. 8). After the mid-1920s, there were increasing trends in both areas up to about 1940, from the early 1950s to the early 1960s and from the early 1970s until the late 1980s. Decreasing trends occurred from about 1940 to the early 1950s and from the early 1960s to the early 1970s. The similarity in the patterns indicates that sea level pressure trends in the North Pacific were closely related to trends in the tropical South Pacific Ocean but were opposite in phase. The trends at Darwin were actual sea level pressures whereas the Aleutian Low Pressure Index is an index of the area of low pressures. The trends of increasing sea level pressures at Darwin, therefore, were associated with trends of increasing size of the area of low pressure in the North Pacific, i.e., with decreasing sea level pressure. This indicates that the pressure trends in the North Pacific Ocean are similar but opposite in phase to the trends in the tropical South Pacific Ocean. We show the period December–May in Fig. 8B; the trend for the period June–November is not shown, but was almost identical to the December–May period.

TABLE 3. Total catches (t) of pink, chum, and sockeye salmon in Asia and North America and catches corrected for interceptions from 1956 to 1975 resulting from Japanese high-seas salmon driftnet fishery. Catch data were obtained from INPFC (1977–89, 1979) and interception data from Fredin (1980).

	Actual catch			Actual catch		Corrected catch	
Year	Asia	North America	Year	Asia	North America	Asia	North America
1925	—	239 600	1956	298 200	148 000	291 386	155 327
1926	462 808	296 700	1957	324 900	141 400	311 157	154 048
1927	227 958	185 600	1958	254 500	167 700	253 695	168 548
1928	493 016	283 700	1959	263 600	104 100	262 244	105 456
1929	301 564	240 000	1960	208 400	113 700	199 425	121 259
1930	470 401	251 900	1961	228 000	160 900	211 894	173 536
1931	342 871	238 100	1962	164 500	177 900	162 286	179 887
1932	399 418	204 000	1963	213 100	143 800	210 870	145 884
1933	291 688	256 000	1964	148 200	166 900	145 731	169 475
1934	500 335	304 700	1965	224 600	138 600	211 091	149 919
1935	391 288	238 100	1966	175 000	197 900	171 307	201 668
1936	432 936	345 700	1967	220 900	115 000	218 899	117 052
1937	503 428	323 200	1968	140 600	180 500	136 928	184 597
1938	503 291	284 200	1969	203 100	119 000	199 301	122 909
1939	595 819	241 600	1970	145 900	203 800	136 497	213 783
1940	311 884	223 900	1971	205 100	159 400	202 025	163 061
1941	442 130	295 500	1972	139 600	133 900	137 415	136 818
1942	330 211	237 400	1973	200 700	138 000	198 881	140 363
1943	417 978	264 400	1974	164 500	104 700	162 290	107 649
1944	235 082	193 700	1975	235 400	86 400	233 697	88 442
1945	166 480	253 600	1976	190 910	150 500	—	—
1946	128 890	209 500	1977	248 020	188 796	—	—
1947	225 040	253 400	1978	182 870	224 351	—	—
1948	130 590	183 400	1979	253 870	243 231	—	—
1949	274 190	240 000	1980	218 140	260 609	—	—
1950	129 130	176 600	1981	254 500	339 427	—	—
1951	272 580	197 400	1982	198 040	289 538	—	—
1952	149 500	168 200	1983	290 520	328 882	—	—
1953	224 900	178 800	1984	233 090	315 698	—	—
1954	178 200	181 600	1985	332 060	392 320	—	—
1955	320 100	145 000	1986	251 500	348 600	—	—
			1987	307 300	282 300	—	—
			1988	252 100	306 100	—	—
			1989	387 100	388 100	—	—

The Nothern Hemisphere surface air temperature anomalies (data from Hansen and Lebedeff 1987) smoothed using a LOWESS band width, f, of 0.20 produced a trend that was also similar to the Aleutian Low Pressure Index (Fig. 8). Temperature anomalies increased just after the turn of the century to about 1940, then decreased until about 1970, and then increased up to the late 1980s. The temperature time series shows the small change in trends in the 1950s that was present in the other indices.

The pattern of marine survival of Japanese hatchery-reared chum salmon, the total catch of chum salmon from the three other salmon producing countries, and the Aleutian Low Pressure Index show similar trends (Fig. 9). The period of increasing marine survival of hatchery-reared salmon was closely associated with an increasing catch of wild chum salmon by the other three Pacific salmon producing countries.

Discussion

The LOWESS and cumulative sum analyses show that similar catch trends exist for the combined all-nation catches of pink, chum, and sockeye salmon and the combined all-nation catches for each species. The changes in these trends occurred at almost the same time throughout the northern North Pacific Ocean. When catch trends were examined by country, the trends persisted, although there was more variation, especially when the catches were relatively small (e.g., sockeye in Russia). The pattern of catches for all species in North America was similar to the pattern of catches in Asia, except that Asia catches did not increase as quickly in the late 1970s and 1980s because of low Russian catches. However, in 1991, Russian catches were the second highest in the time series, indicating that the trends in Asian salmon production were similar to North American trends.

The strong similarity of the pattern of pink, chum, and sockeye salmon catches indicates that common events affect the production of salmon in the North Pacific Ocean. These common events influence catch over a vast area despite high fishing effort, different fleet dynamics, different gear, and different management policies. The Aleutian Low is a large-scale climate system that affects vast areas of the northern North Pacific Ocean. Our index of the intensity of this system closely matched the trend in all-nation salmon production.

There is considerable variation among the life histories of pink, chum, and sockeye salmon as well as some variation in life history within each species. Climate variation, therefore, can influence survival over a number of years, making it difficult to identify correlations between salmon survival and envi-

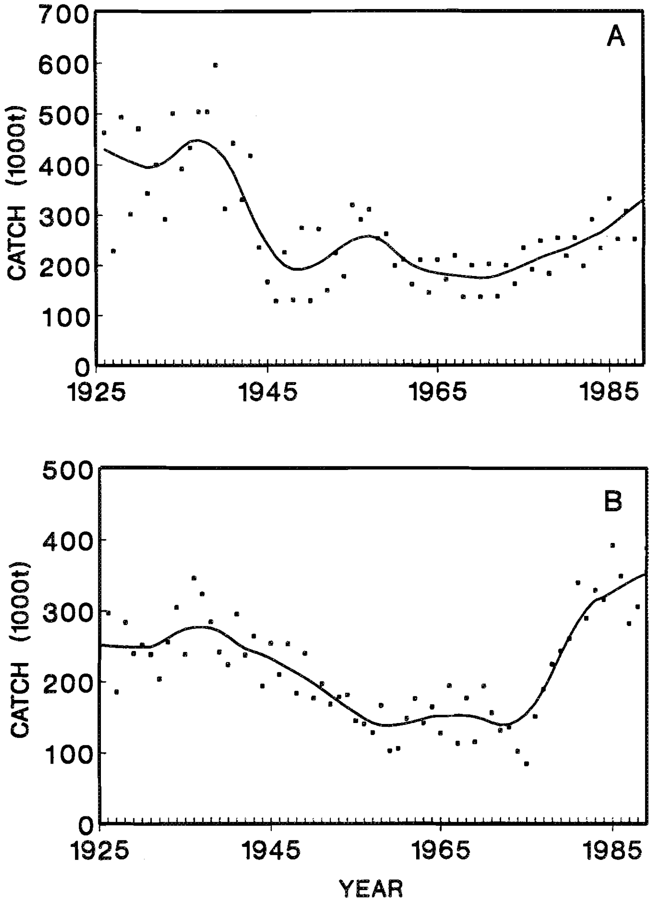

FIG. 6. Trends in catches of the combined (A) Asian and (B) North American catches of pink, chum, and sockeye salmon. The solid squares in Fig. 6B are the mean annual catches adjusted for high-seas interceptions (see text), and the solid line in both panels is the LOWESS smoother with a band width, *f*, of 0.20.

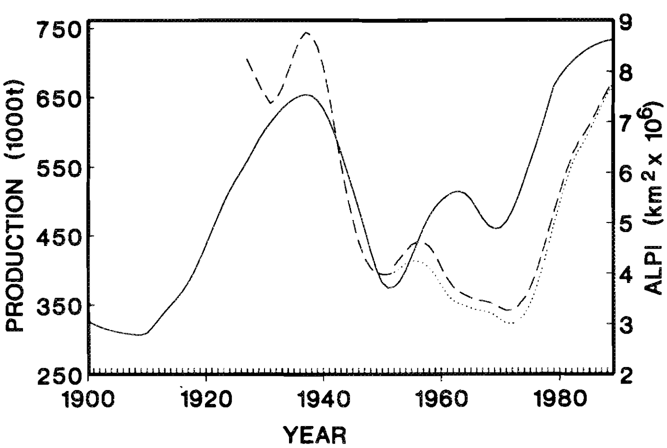

FIG. 7. Comparison of the combined all-nation catch (production) of pink, chum, and sockeye salmon, including lost production resulting from the high-seas salmon driftnet fishery (broken line) and the smoothed Aleutian Low Pressure Index (solid line), produced using a LOWESS smoother with a band width, *f*, of 0.20, from the annual values in Table 4. The dotted line represents the smoothed all-nation catch that is not adjusted for lost production resulting from high-seas interceptions.

TABLE 4. Annual Aleutian Low Pressure Index (km^2) for winter and spring for the years 1900–89. Data for December–May.

Year	Aleutian Low	Year	Aleutian Low
1900	6 660 225	1945	No data
1901	1 871 775	1946	8 732 025
1902	6 323 400	1947	2 132 775
1903	0	1948	2 371 275
1904	8 775	1949	3 011 625
1905	4 000 050	1950	1 685 250
1906	2 589 750	1951	3 047 850
1907	0	1952	1 984 050
1908	4 484 475	1953	9 560 475
1909	1 938 375	1954	3 785 175
1910	0	1955	2 679 525
1911	0	1956	255 600
1912	7 933 275	1957	3 125 025
1913	3 875 850	1958	10 322 550
1914	8 973 675	1959	2 909 475
1915	1 356 975	1960	6 738 975
1916	0	1961	10 583 325
1917	3 529 575	1962	3 803 850
1918	5 504 625	1963	10 542 825
1919	7 616 250	1964	7 713 000
1920	27 000	1965	2 834 100
1921	5 858 100	1966	4 033 575
1922	143 550	1967	6 862 950
1923	3 840 750	1968	4 968 225
1924	6 446 475	1969	1 274 625
1925	5 290 650	1970	10 449 900
1926	14 023 800	1971	129 825
1927	8 216 550	1972	1 800
1928	7 562 475	1973	2 335 050
1929	8 777 475	1974	5 881 725
1930	1 669 950	1975	5 673 825
1931	11 310 300	1976	6 165 900
1932	1 731 600	1977	11 306 025
1933	3 368 475	1978	10 462 950
1934	10 867 275	1979	4 457 925
1935	6 318 000	1980	11 967 525
1936	11 192 625	1981	13 409 775
1937	1 024 200	1982	2 475
1938	7 877 700	1983	13 959 000
1939	7 605 450	1984	6 321 150
1940	15 435 225	1985	5 001 075
1941	13 852 800	1986	12 646 125
1942	9 082 575	1987	10 624 050
1943	2 581 875	1988	8 901 225
1944	8 431 875	1989	2 632 050

ronmental variation. The low correlations between the annual Aleutian Low Pressure Index and annual salmon production, either lagged or unlagged, indicate that the annual relationship between all-nation salmon production and the Aleutian Low Pressure Index is highly variable either because climate-induced productivity changes occur over a number of years or there is much interannual variation not explained by the general climate index or both. We did examine correlations based on 5-, 7-, and 11-yr running averages of the Aleutian Low Pressure Index and annual all-nation salmon catches of all species. The correlations were considerably higher; however, analyzing data in this manner creates new sets of problems that we felt were better left for another paper.

It is possible that factors other than the environment affected the production trends. For example, overfishing during the early high-production period (1925–40) may have reduced production and resulted in the observed long period of low catches

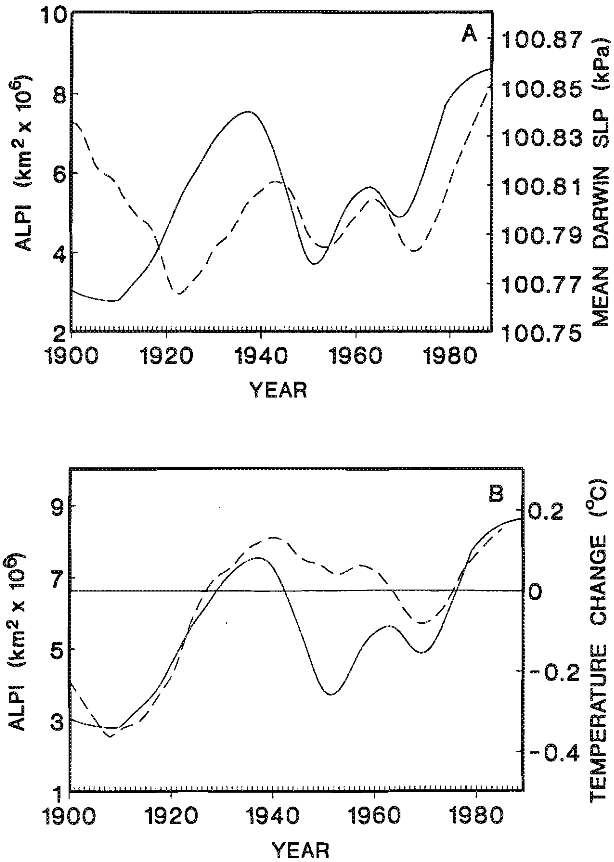

FIG. 8. (A) Aleutian Low Pressure Index (solid line) compared with sea level pressure at Darwin (broken line), smoothed using a LOWESS smoother with a band width, f, of 0.20. (B) Northern Hemisphere mean surface air temperature anomalies smoothed using a LOWESS smoother with a band width, f, of 0.20 (broken line) compared with the Aleutian Low Pressure Index (solid line).

from 1945 to 1975. It is difficult to compare returns per spawner for the stocks involved and for the time series we used. However, when we examined the Japanese hatchery data, there was evidence that indicated that production of salmon from the early 1970s to the present was associated with improved marine survival. Higher pink salmon survival of both hatchery and wild stocks in Alaska during this same period was associated with higher ocean temperatures during the early marine period (Willette and Cooney 1991 and unpublished data; D.M. Eggers et al.[2]). However, the most convincing argument that trends are not the result of management actions in response to overfishing is the consistent similarity among trends. It is unlikely that overfishing periods would be similar among the four countries for all three species and that at about the same time, each management agency in each country would initiate programs of rebuilding that resulted in an almost simultaneous improvement in abundance.

Artifical rearing or enhancement activities may have contributed to the increases in production starting in the mid-1970s. Our data series ends in 1989, so brood years (year of spawning) of sockeye and chum salmon in the 1989 catch occurred in the mid-1980s (most sockeye salmon return to spawn at age 4 and

[2]Paper presented at the International Symposium on Biological Interactions of Enhanced and Wild Salmonids, June 1991, Nanaimo, B.C. (unpublished).

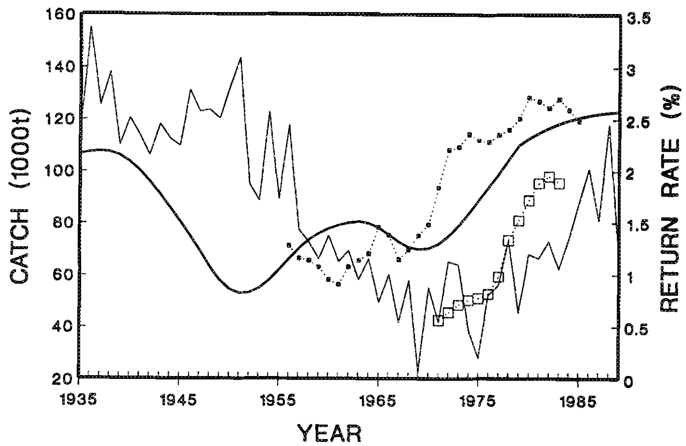

FIG. 9. Total annual North Pacific Ocean catch of chum salmon (not smoothed) by Canada, the United States, and Russia (solid line) compared with Japanese hatchery-reared chum survival rates for Hokkaido (solid squares) and Honshu (open squares). The survival rates are shown as 5-yr means. The heavy solid line is the smoothed Aleutian Low Pressure Index from Fig. 7.

5, and most chum salmon return to spawn at ages 4–6) and pink salmon in the late 1980s (almost all pink salmon return after 18 mo at sea).

In Japan, chum salmon production is now exclusively from hatcheries. From 1972 to 1982, releases of chum salmon fry from hatcheries increased from 800 million to 2 billion fry (M. Keriyama[1]). Marine survival of these fry increased from 1 to 2% in about 1966, apparently because of changes in hatchery practices (Kaeriyama 1989). In 1976, 1977, and 1981, the marine survival was exceptionally high at 3% (M. Kaeriyama[1]). Pink salmon are also produced in Japanese hatcheries, but production is relatively small (138 million fry in 1989 or about 6400 t of returning adults using an average marine survival of 1.5% and an average weight in the coastal fishery of 1.6 kg). M. Kaeriyama[1] noted that the highest marine survival of hatchery-reared pink salmon of 3.8% occurred for pink salmon going to sea in 1977. Our comparison of catches of chum salmon by Canada, the United States, and Russia (Fig. 9) with changes in the marine survival of chum reared in Japanese hatcheries shows a similar pattern between climate change and marine survival. There is no question that the increasing catches of chum salmon in Japan in the 1970s were a result of increasing hatchery production, but the increase in marine survival in the late 1970s and early 1980s indicated that there were changes in the marine environment that contributed to this improved survival.

Salmon hatcheries in Russia produced about 480 million pink salmon fry and 320 million chum salmon fry in the 1970s and about 25% fewer fry in the 1980s (V.M. Chupakhin et al.[3]). From 1976 to 1990, catches of chum salmon increased (V.M. Chupakhin et al.[3]) despite reductions in releases from hatcheries, indicating that survival of hatchery fish in the marine environment improved. Using an average marine survival estimate of 1.5% for pink salmon and 1% for chum salmon, and an average weight of 1.6 kg for pink and 3.6 kg for chum, we estimated that hatchery production in Russia could account for an annual production of about 9000 t of chum salmon and 9000 t of pink salmon in the mid-1980s. This production would

[3]Paper presented at the International Symposium on Biological Interactions of Enhanced and Wild Salmonids, June 1991, Nanaimo, B.C. (unpublished).

be a significant amount of the chum salmon catch, if harvest rates were high (70–90%), but not of the pink salmon catch. Thus, the addition of hatchery-produced pink salmon would not explain the increased catches that began in the late 1970s.

Alaska is the major producer of salmon caught in the United States. In the central Gulf of Alaska, hatchery-produced pink salmon contributed about 5% of the total pink salmon biomass in 1980 and 27% of the total biomass in 1985 (D.M. Eggers et al.[2]). Thus, hatchery production contributed to the increases in catch from the early to mid-1980s. However, production from the wild runs also increased three to four times from the mid-1970s to the mid-1980s (D.M. Eggers et al.[2]). In the mid-1980s, approximately 3300 t of adult chum salmon and 2100 t of adult sockeye salmon were produced from Alaskan fisheries enhancement programs (estimates made from total releases in 1983, assuming a marine survival rate of 1% for chum and sockeye salmon and an average weight of chum salmon of 3.6 kg and sockeye of 3.2 kg). The increases in catch of both chum and sockeye salmon in the late 1970s were so large that the contribution from hatcheries and enhancement would represent only a small amount of the increased production.

In Canada, pink salmon hatchery production was relatively small, contributing less than 500 t up to the mid-1980s. The average increases in total catch from the mid-1970s to mid-1980s would therefore not be a direct result of enhancement. Sockeye salmon enhancement from 1975 to 1980 resulted in an annual increase in catch of about 1500 t by 1980 and 3000 t by 1985 (Salmon Enhancement Program, Vancouver, B.C., Canada, unpublished data). This would be an important contribution to the increase in catch but would not account for the average increase in catch from 1975 to 1985. Hatchery production of chum salmon in the Canadian commercial catch increased from about 200 t in the mid-1970s to about 7000 t in 1985. Chum salmon catches that increased in the mid-1980s appear to be associated with the increased catch of enhanced fish. The Canadian contribution of chum salmon to the total all-nation catch, however, was only about 8% during this period.

It is difficult to separate the increases in salmon abundance resulting from improved ocean survival from increases in abundance that could result from improvements in productivity in the freshwater environment. Because the increases in salmon survival in the late 1970s occurred at the same time that year classes of a number of other commercially important marine fishes had exceptionally high marine survival (Beamish 1993), it appears that there was a general increase in production of commercially important marine fish species beginning in the late 1970s. The reason for the exceptionally strong year classes of marine fishes is believed to be the large increases in food for larval fishes that occurred in the late 1970s (Brodeur and Ware 1992; McFarlane and Beamish 1992; Beamish 1993). We reexamined the relationship reported by McFarlane and Beamish (1992) using updated annual Aleutian Low Pressure Index data for the 6-mo period December–May and the unweighted mean monthly (March–May) copepod abundance estimates for ocean station P (50°N, 145°W; Fig. 2). We used a standard linear regression because the residuals were not significantly autocorrelated at the 5% level. We found that there was a significant relationship between copepod abundance and the Aleutian Low Pressure Index (Fig. 10; $r = 0.50$, $p < 0.05$). Although this relationship was not as strong as estimated by McFarlane and Beamish (1992), it shows that there is a close relationship between the average intensity of the Aleutian Low and the average production of copepods. The average annual production of copepods from 1965 to 1975 was 86.6/m^3 compared to 129.8/m^3 from 1976 to 1980, a 1.5 times increase in abundance. If we used our calculated relationship to estimate copepod abundance from 1981 to 1989, the extrapolated estimates would indicate a 5–6 times increase in abundance if the relationship continues outside the range of the data. We believe that the differences in average copepod production between the two periods are evidence that there was a large increase in the abundance of copepods beginning in 1976 that was associated with the change towards more intense Aleutian Lows (Fig. 7). Because copepods are a principle food for many marine species, including salmon and prey of salmon, and because copepods are the dominant species in the zooplankton (McFarlane and Beamish 1992), we believe that increases in salmon production are closely related with the increases in zooplankton production in the marine environment.

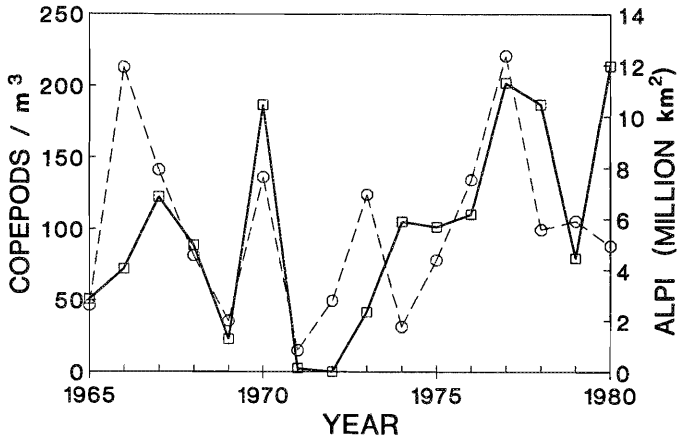

FIG. 10. Relationship between copepod abundance at Ocean Station P (broken line) and the Aleutian Low Pressure Index (solid line). Data not smoothed.

If climate over the northern North Pacific Ocean affects survival of Pacific salmon and results in long-term trends in production, there should be evidence of density-dependent growth. Such a carrying-capacity effect would likely be related to food availability on a large geographic scale. Ishida et al. (1993) showed significant increases in mean age of Japanese and Russian chum salmon stocks and decreases in mean body weight. These changes occurred during the period of increasing abundance in the 1970s and 1980s. Rogers (1980) and Peterman (1984) have also identified density-dependent growth in North American stocks of sockeye salmon. Thus, although the evidence is limited, there are examples of density-dependent growth during the 1980s. It is interesting that the trend towards decreasing size occurred during a period when food apparently was increasing. A relationship between decreasing fish size and increasing ocean productivity trends would also be expected to result in increases in the trends of fish size during periods of decreasing trends in productivity.

We concluded that the trends in salmon production from 1925 to 1989 were not primarily a result of fishing effort, management actions, or artificial rearing, but rather that the trends in abundance were strongly linked to the environment. The robustness of the general trend in the three species for all countries over such a vast geographical area, the continuous rather than precipitous change in abundance, and the close association of the trends with trends in the Aleutian Low suggest that this vast low pressure system is associated with the changes in salmon abundance. The mechanism involved could result from increased upwelling in the ocean under the centre of the Aleutian Low (Reid 1962; Thompson 1981) resulting in increased productivity (Venrick et al. 1987; Brodeur and Ware 1992; McFarlane and Beamish 1992). The resulting horizontal divergence (Reid 1962) would transport plankton and nutrients along the edge of the coast of North America. Off the Pacific coast of Asia, it is known that north–south shifts in the Aleutian Low affect winter sea surface temperatures in the western North Pacific Ocean off the coast of Japan and the strength of the East Asian Winter Monsoon over Japan (Hanawa et al. 1989). A northern shift in the Aleutian Low produces warmer winters and weaker East Asian Winter Monsoons, while a southern shift in the Aleutian Low produces colder winter sea surface temperatures and stronger East Asian Winter Monsoons (Hanawa et al. 1989), confirming that the strength and position of the Aleutian Low affect ocean conditions along the Asian coast. We are not aware of any studies that relate changes in the intensity of the Aleutian Low with plankton production along the Asian coast; however, the relationship between the position of the Aleutian Low and large-scale effects on sea surface temperatures in the western North Pacific Ocean shown by Hanawa et al. (1989) suggests that the intensification of the Aleutian Low could effect the productivity of vast areas of the northern North Pacific Ocean.

The smoothed trend in the Aleutian Low Pressure Index was similar to the smoothed trend in sea surface pressure at Darwin after the mid-1920s (Fig. 8A) and to the trend in the Northern Hemisphere mean sea surface temperature change (Hansen and Lebedeff 1987) (Fig. 8B), indicating an association among the climate indicies. The use of the Hansen and Lebedeff (1987) temperature series shows trends that are similar to the Aleutian Low Pressure Index, but it over simplifies the pattern of sea surface temperature trends. McLain (1984) and Trenberth (1990) both showed that the pattern of sea surface temperature anomalies tends to be opposite along the west coast of Canada and the United States compared with the open ocean. Trenberth and Paolino (1981) and Niebauer (1988) suggested that climate changes reflected by differences in sea surface pressure between Darwin and Tahiti (the Southern Oscillation Index) are linked to climate anomalies in the Northern Hemisphere and Bering Sea by the Aleutian Low pressure system. The parallel smoothed trends of the sea surface pressure at Darwin and the Aleutian Low Pressure Index are opposite in phase, indicating that an oscillation in pressure trends occurs between the tropical South Pacific Ocean and North Pacific Ocean and are additional evidence that a linkage exists between the climate trends in these two areas.

Climate events over the tropical South Pacific Ocean are associated with sea surface temperatures in the northern North Pacific Ocean and the Bering Sea (Iwasaka et al. 1987; Yasunari 1987a, 1987b; Hanawa et al. 1988; Niebauer 1988). Sea surface temperatures, therefore, as well as sea surface pressures are linked between the South and the North Pacific through the atmospheric circulation and the intensification of the Aleutian Low (Namias 1959, 1963, 1969; Davis 1976, 1978; Blackmon et al. 1983; Lazante 1984; Wallace et al. 1990; Alexander 1992a, 1992b). We point out the similarity in the trends in these indices of sea surface pressure, land temperatures, and the associations between climate events in the South and North Pacific to show that salmon production trends may be associated with climate variables other than the Aleutian Low Pressure Index and with climate events in areas other than the North Pacific Ocean.

The Aleutian Low Pressure Index was the lowest in the time series at the turn of the century. Trenberth and Paolino (1980) showed that the sea level pressure data were most reliable after 1924; however, if the index is valid for the early part of the time series and if it followed the same relationship with salmon abundance up to 1925 as it did after 1925, then the all-nation salmon abundance must have been low just after the turn of the century. It is difficult to confirm if this reduced abundance occurred because modern salmon fisheries were just developing and catch records, when they exist, are not necessarily reliable indicators of total abundance. In Japan, Kaeriyama (1989) reported that the wild fishery for chum salmon in Hokkaido was in an early development phase beginning in 1870 and reaching a maximum of 11 million individuals in 1889. Catches declined sharply over the next 20 yr, as a result of declining stock abundance, to a low of 1.2 million fish in 1909. The decline was believed to have occurred because of overfishing and poor hatchery practices. Hatcheries started in 1887 and by 1892 were releasing 16 million fish; thus, it is possible that the hatchery program was affecting wild fish production. Nevertheless, there was a dramatic decline in the catch of the Hokkaido fishery at the turn of the century. However, there was only a small increase in production in the 1920s and 1930s when the Aleutian Low Pressure Index was increasing. The factors affecting catches are not known, but it does appear that production declined at the turn of the century. In Canada and the United States, the early salmon fishery occurred mostly for sockeye salmon in the vicinity of the Fraser River and Bristol Bay. The Fraser River stocks were believed to have declined beginning in 1898 for low-cycle runs and after 1913 for all runs (Gilbert 1918; Rounsefell and Kelez 1938; Ricker 1987). The decline in abundance before 1913 was believed to result from overfishing and after 1913 from a combination of overfishing and the obstruction caused by a rockslide in 1913 (Gilbert 1918; Rounsefell and Kelez 1938; Ricker 1987). In the United States, in Bristol Bay, the sockeye salmon fishery developed rapidly in the late 1890s and by 1913 was about 20 million fish (Minard and Meacham 1987). Catches of about 16 million sockeye salmon were sustained until the late 1930s. There was no decline in catch at the turn of the century, possibly because the fishery was still developing. Thus, it is difficult to unravel the reasons for the trends in catches of salmon at the beginning of the salmon fishery in the late 1800s, but it is also difficult to dismiss the possibility that abundance at this time was low, as might be indicated by the trend in the Aleutian Low Pressure Index for the early part of the time series.

Total all-nation catches show that pink, chum, and sockeye salmon production varied from 837 400 to 275 600 t from 1925 to 1989. Our study indicates that this variation in production is associated with trends in the environment. The pattern of the Aleutian Low Pressure Index indicates that eventually it will become less intense (i.e., a return to higher pressures). In the most recent years, there have been some less intense Aleutian Lows, possibly indicating a weakening trend. If this weakening trend remains and if other factors such as increased ocean temperatures do not change the relationship between the Aleutian Low Pressure Index and Pacific salmon abundance, we would predict that Pacific salmon abundance will begin to decline.

Changes in trends in production, possibly as a result of shifts in the structure of ecosystems, have a direct effect on salmon management. The production trends identified in this study indicate that it is not appropriate to assume that the factors regulating salmon populations have been more or less constant or have varied randomly over the time series in this study. Furthermore, the trends indicate that the management of salmon should be focused on larger aggregates of stocks as well as individual stocks. Strategies for artificially rearing Pacific salmon to improve catches should also consider the effects of production trends. Hatchery production appears to have followed the trends in wild production in the 1970s and 1980s and may have assisted in the rate of increase of abundance by providing large numbers of smolts at a time of improved marine survival. However, when production trends change, it may not be an appropriate strategy to continue to release large numbers of artificially reared smolts during a period of decreasing marine survival of salmon. It is important to recognize and understand the causes of large-scale, long-term patterns in salmon abundance because declines in marine survival should be managed differently from declines resulting from fishing mortality that is too high.

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References

Alexander, M. 1992a. Midlatitude atmosphere–ocean interaction during El Niño. Part I. The North Pacific Ocean. J. Clim. 5: 944–958.

Alexander, M. 1992b. Midlatitude atmosphere–ocean interaction during El Niño. Part II. The Northern Hemisphere atomosphere. J. Clim. 5: 959–972.

Beamish, R.J. 1993. Climate and exceptional fish production off the west coast of North America. Can. J. Fish. Aquat. Sci. 50. (In press)

Blackmon, M.L., J.E. Geisler, and E.J. Pitcher. 1983. A general circulation model study of January climate anomaly patterns associated with interannual variation of equatorial Pacific sea surface temperatures. J. Atmos. Sci. 40: 1410–1425.

Brodeur, R.D., and D.M. Ware. 1992. Long-term variability in zooplankton biomass in the subarctic Pacific Ocean. Fish. Oceanogr. 1: 32–38.

Burgner, R.L. 1991. Life history of sockeye salmon (*Oncorhynchus nerka*), p. 1–117. *In* C. Groot and L. Margolis [ed.] Pacific salmon life histories. University of British Columbia Press, Vancouver, B.C.

Campbell, A., D.J. Noakes, and R.W. Elner. 1991. Temperature and lobster, *Homarus americanus*, yield relationships. Can. J. Fish. Aquat. Sci. 48: 2073–2082.

Cleveland, W.J. 1985. The elements of graphing data. Wadsworth Inc., California. 323 p.

Davis, R. 1976. Predictability of sea surface temperature and sea level pressure anomalies over the North Pacific Ocean. J. Phys. Oceanogr. 6: 249–266.

Davis, R. 1978. Predictability of sea-level pressure anomalies over the North Pacific Ocean J. Phys. Oceanogr. 8: 233–246.

Ebbesmeyer, C.C., C.A. Coomes, G.A. Cannon, and D.E. Bretschneider. 1989. Linkage of ocean and fjord dynamics at decadal period. Geophys. Monogr. 55: 399–417.

Foerster, R.E. 1968. The sockeye salmon, *Oncorhynchus nerka*. Bull. Fish. Res. Board Can. 162: 422 p.

Fredin, R.A. 1964. Ocean mortality and maturity schedules of Karluk River sockeye salmon and some comparison of marine growth and mortality rates. Fish. Bull. U.S. 63: 551–574.

Fredin, R.A. 1980. Trends in North Pacific salmon fisheries, p. 59–119. *In* W.J. McNeil and D.C. Himsworth [ed.] Salmonid ecosystems of the North Pacific Ocean. Oregon State University, Corvallis, OR.

Friis-Christensen, E., and K. Lassen. 1991. Length of the solar cycle: an indicator of solar activity closely associated with climate. Science (Wash., DC) 254: 698–700.

Gilbert, C.H. 1918. Contributions to the life-history of the sockeye salmon. Rep. B.C. Comm. Fish. 1917: 33–80.

Hamilton, K. 1984. Seasonal mean North Pacific sea level pressure charts 1939–1982. Manuscr. Rep. No. 41. Department of Oceanography, University of British Columbia, Vancouver, B.C. 177 p.

Hanawa, K., T. Watanabe, N. Iwasaka, T. Suga, and Y. Toba. 1988. Surface thermal conditions in the western North Pacific during ENSO events. J. Meteorol. Soc. Jpn. 66: 445–456.

Hanawa, K., Y. Yoshikawa, and T. Watanabe. 1989. Composite analyses of wintertime wind stress vector fields with respect to SST anomalies in the Western North Pacific and the ENSO events. Part 1: SST composite. J. Meteorol. Soc. Jpn. 67: 385–399.

Hansen, J., and S. Lebedeff. 1987. Global trends of measured surface air temperature. J. Geophys. Res. 92: 13345–13372.

Heard, W.R. 1991. Life history of pink salmon (*Oncorhynchus gorbuscha*). p. 119–230. *In* C. Groot and L. Margolis [ed.] Pacific salmon life histories. UBC Press, Vancouver, B.C.

International North Pacific Fisheries Commission (INPFC). 1977–89. INPFC statistical yearbooks, 1977–1989.

International North Pacific Fisheries Commission (INPFC). 1979. Historical catch statistics for salmon of the North Pacific Ocean. INPFC Bull. No. 39.

Ishida, Y., S. Ito, M. Kaeriyama, S. McKinnell, and K. Nagasawa. 1993. Recent changes in age and size of chum salmon (*Oncorhynchus keta*) in the North Pacific Ocean and possible causes. Can. J. Fish. Aquat. Sci. 50: 290–295.

Iwasaka, N., K. Hanawa, and Y. Toba. 1987. Analysis of SST anomalies in the North Pacific and their relation to 500 mb height anomalies over the Northern Hemisphere during 1969–1979. J. Meteorol. Soc. Jpn. 65: 103–114.

Jones, P.D., S.C.B. Raper, and T.M.L. Wigley. 1986. Southern hemisphere surface air temperature variations: 1851–1984. J. Clim. Appl. Meteorol. 25: 1213–1230.

Kaeriyama, M. 1989. Aspects of salmon ranching in Japan. Physiol. Ecol. Jpn. Spec. Vol. 1: 625–638.

Lanzante, J.R. 1984. A rotated eigenanalysis of the correlation between 700-mb heights and sea surface temperatures in the Pacific and Atlantic. Mon. Weather Rev. 112: 2270–2280.

Margolis, L. 1990. Notes on high-seas distribution of Canadian salmonids and the Japanese high-seas salmon fisheries. (Available from the Pacific Biological Station, Nanaimo, B.C.)

McFarlane, G., and R.J. Beamish. 1992. Climatic influence linking copepod production with strong year-classes in sablefish, *Anoplopoma fimbria*. Can. J. Fish. Aquat. Sci. 49: 743–753.

McLain, D.R. 1984. Coastal ocean warming in the Northeast Pacific, 1976–83, p. 61–86. *In* W.G. Pearcy [ed.] The influence of ocean conditions on the production of salmonids of the North Pacific. Oregon State University Sea Grant College Program ORESU-W-83-001.

Minard, R.E., and C.P. Meacham. 1987. Sockeye salmon (*Oncorhynchus nerka*) management in Bristol Bay, Alaska, p. 336–342. *In* H.D. Smith, L. Margolis, and C.C. Wood [ed.] Sockeye salmon (*Oncorhynchus nerka*) population biology and future management. Can. Spec. Publ. Fish. Aquat. Sci. 96.

Murdoch, J. 1979. Control charts. MacMillan Press Ltd., London. 150 p.

Namias, J. 1959. Recent seasonal interactions between North Pacific waters and the overlying atmospheric circulation. J. Geophys. Res. 64: 631–646.

Namias, J. 1963. Large-scale air–sea interactions over the North Pacific from summer 1962 through the subsequent winter. J. Geophys. Res. 68: 6171–6786.

Namias, J. 1969. Seasonal interactions between the North Pacific Ocean and the atmosphere during the 1960s. Mon. Weather Rev. 97: 173–192.

Neave, F., T. Yonemori, and R.G. Bakkala. 1976. Distribution and origin of chum salmon in offshore waters of the North Pacific Ocean. INPFC Bull. No. 35.

Niebauer, H.J. 1988. Effects of El Niño – southern oscillation and north Pacific weather patterns on interregnal variability in the subarctic Bering Sea. J. Geophys. Res. 93: 5051–5068.

Parker, R.R. 1963. On the problem of maximum yield from north Pacific sockeye salmon stocks. J. Fish. Res. Board Can. 20: 1371–1396.

Peterman, R.M. 1984. Density-dependent growth in early life of sockeye salmon. Can. J. Fish. Aquat. Sci. 41: 1825–1829.

Reid, G.C. 1987. Influence of solar variability on global sea surface temperatures. Nature (Lond) 329: 142–143.

Reid, J.L. Jr. 1962. On circulation, phosphate-phosphorus content, and zoop. volumes in the upper part of the Pacific Ocean. Limnol. Oceanogr. 7: 287–306.

Ricker, W.E. 1954. Stock and recruitment. J. Fish. Res. Board Can. 11: 559–623.

Ricker, W.E. 1964. Ocean growth and mortality of pink and chum salmon.

J. Fish. Res. Board Can. 21: 905–931.

RICKER, W.E. 1976. Review of the rate of growth and mortality of Pacific salmon in salt water, and non-catch mortality caused by fishing. J. Fish. Res. Board. Can. 33: 1483–1524.

RICKER, W.E. 1987. Effects of the fishery and of obstacles to migration on the abundance of Fraser River sockeye salmon (*Oncorhynchus nerka*). Can. Tech. Rep. Fish. Aquat. Sci. 1522: 75 p.

ROGERS, D.E. 1980. Density-dependent growth of Bristol Bay Sockeye salmon, p. 267–283. *In* W.J. McNeil and D.C. Himsworth [ed.] Salmonid ecosystems of the North Pacific. Oregon State University Press, Corvallis, OR.

ROUNSEFELL, G.A., AND G.B. KELEZ. 1938. The salmon and salmon fisheries of Swiftsure Bank, Puget Sound, and the Fraser River. Bull. U.S. Bur. Fish. 49: 693–823.

ROYER, T.C. 1982. Coastal fresh water discharge in the Northeast Pacific. J. Geophys. Res. 87: 2017–2021.

SALO, E.O. 1991. Life history of chum salmon (*Oncorhynchus keta*), p. 231–309. *In* C. Groot and L. Margolis [ed.] Pacific salmon life histories. UBC Press, Vancouver, B.C.

SHEPARD, M.P., C.D. SHEPARD, AND A.W. ARGUE. 1985. Historic statistics of salmon production around the pacific rim. Can. MS Rep. Fish. Aquat. Sci. 1819: 297 p.

TAKAGI, K., K.V. ARO, A.C. HARTT, AND M.B. DELL. 1981. Distribution and origin of pink salmon (*Oncorhynchus gorbuscha*) in offshore waters of the North Pacific Ocean. INPFC Bull. No. 40: 195 p.

THOMSON, R.E. 1981. Oceanography of the British Columbia Coast. Can. Spec. Publ. Fish. Aquat. Sci. 56: 291 p.

TRENBERTH, K.E. 1990. Recent observed interdecadal climate changes in the Northern Hemisphere. Bull. Am. Meteorol. Soc. 71: 988–993.

TRENBERTH, K.E., AND D.A. PAOLINO. 1980. The Northern Hemisphere sea-level pressure data set: trends, errors and discontinuities. Mon. Weather Rev. 108: 855–872.

TRENBERTH, K.E., AND D.A. PAOLINO. 1981. Characteristic patterns of variability of sea level pressure in the Northern Hemisphere. Mon. Weather Rev. 109: 1169–1189.

VENRICK, E.L., J.A. MCGOWAN, D.R. CAYAN, AND T.L. HAYWARD. 1987. Climate and chlorophyll *a*: long-term trends in the Central North Pacific Ocean. Science (Wash., DC) 238: 70–72.

WALLACE, J.M., C. SMITH, AND Q. JIANG. 1990. Spatial patterns of atmosphere–ocean interaction in the northern winter. J. Clim. 3: 990–998.

WILLETTE, T.M., AND R.T. COONEY. 1991. An empirical orthogonal functions analysis of sea surface temperature anomalies in the North Pacific Ocean and cross correlations with pink salmon (*Oncorhynchus gorbuscha*) returns to southern Alaska, p. 111–121. *In* B. White, and I. Guthrie [ed.] Proceedings of the 15th Northeast Pacific pink and chum salmon workshop, Vancouver, B.C.

YASUNARI, T. 1987a. Global structure of the El Niño/Southern Oscillation. Part I. El Niño composites. J. Meteorol. Soc. Jpn. 65: 67–80.

YASUNARI, T. 1987b. Global structure of the El Niño/Southern Oscillation. Part II. Time evolution. J. Meteorol. Soc. Jpn. 65: 81–102.