A Relationship between Fraser River Discharge and Interannual Production of Pacific Salmon (*Oncorhynchus* spp.) and Pacific herring (*Clupea pallasi*) in the Strait of Georgia

Richard J. Beamish, Chrys-Ellen M. Neville, and Barbara L. Thomson

Department of Fisheries and Oceans, Pacific Biological Station, Hammond Bay Rd., Nanaimo, BC V9R 5K6, Canada

and Paul J. Harrison and Mike St. John

Department of Oceanography, University of British Columbia, 6270 University Blvd., Vancouver, BC V6T 1W5, Canada

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We identified years of anomalously high and low discharge from the Fraser River and compared these years with indices of anomalously high and low production of Pacific salmon (*Oncorhynchus* spp.) and Pacific herring (*Clupea pallasi*). For chinook (*O. tshawytscha*) and coho salmon (*O. kisutch*), we found that brood years that went to sea in a year when the Fraser River discharge was very high compared with the previous year virtually never had an index of production that was higher than the previous year. Similarly, brood years that went to sea in a year when the Fraser River discharge was very low compared with the previous year almost never had an index of productivity that was lower than the previous year. The analysis identified a weaker association between extreme discharge anomalies and chum salmon (*O. keta*) production. A close association was not found between extreme discharge anomalies and pink salmon (O. *gorbuscha*), sockeye salmon (*O. nerka*), or herring production. The relationships identify a connection between annual fluctuations in river flow and production of some marine fishes and may be of use in forecasting abundance changes.

Nous avons repéré des années où le débit du Fraser était anormalement élevé ou bas et mis en relation ces années avec des indices de production anormalement élevés ou bas chez les saumons du Pacifique (*Oncorhynchus* spp.) et le hareng du Pacifique *Clupea pallasi*. Dans les cas du quinnat (*O. tshawytscha*) et du coho (*O. kisutch*), nous avons observé que l'indice de production des contingents qui effectuaient leur avalaison dans une année où le débit du Fraser était très élevé par rapport à celui de l'année précédente n'était pour ainsi dire jamais supérieur à l'indice des contingents de l'année précédente. De même, l'indice de production des contingents qui effectuaient leur avalaison dans une année où le débit du Fraser était très bas par rapport à celui de l'année précédente n'était pour ainsi dire jamais inférieur à l'indice des contingents de l'année précédente. La corrélation entre les débits extrêmes et la production chez le kéta (*O. keta*) était plus faible. Enfin, on n'a pas observé de corrélation serrée entre ces deux paramètres dans les cas du saumon rose (O. *gorbuscha*), du saumon rouge (*O. nerka*)) et du hareng. Ces analyses ont permis d'établir l'existence d'une relation entre les fluctuations interannuelles du débit et la productivité de certaines espèces de poissons marins, relation qui pourrait être prise en considération dans la prévision des variations d'abondance.

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The Strait of Georgia, located between Vancouver Island and the British Columbia mainland (Fig. 1), is an important marine ecosystem on Canada's west coast and one of the most important salmon-producing areas in the Pacific Ocean. There are five species of Pacific salmon that are resident in or move through the Strait of Georgia: pink (*Oncorhynchus gorbuscha*), chum (*O. keta*), sockeye (*O. nerka*), coho (*O. kisutch*), and chinook (*O. tshawytscha*). Most of the production of these five species comes from the Fraser River which produces more Pacific salmon than any other river in British Columbia. For the 5-yr period 1986–90, approximately 32% of the average total Canadian catch of Pacific salmon or approximately 41% of the total catch in a year of Fraser River pink salmon returns originated from the Fraser River.

The Strait of Georgia is 220 km long, 33 km wide, has a surface area of about 6900 km^2, an average depth of 155 m, and a maximum depth of 420 m (Waldichuk 1957). It 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 (Waldichuk 1957). The total volume of the freshwater discharge reduces the surface salinity, and because of the reduced salinity and the semienclosed nature of the strait, it could be considered a large estuary according to the definition of Pritchard (1967). Discharge from the Fraser River establishes the estuarine circulation of less-dense surface water flowing out of the strait, compensated by deep water flowing into the strait from offshore. This deep water enters through Juan de Fuca Strait (Thomson 1981) and the

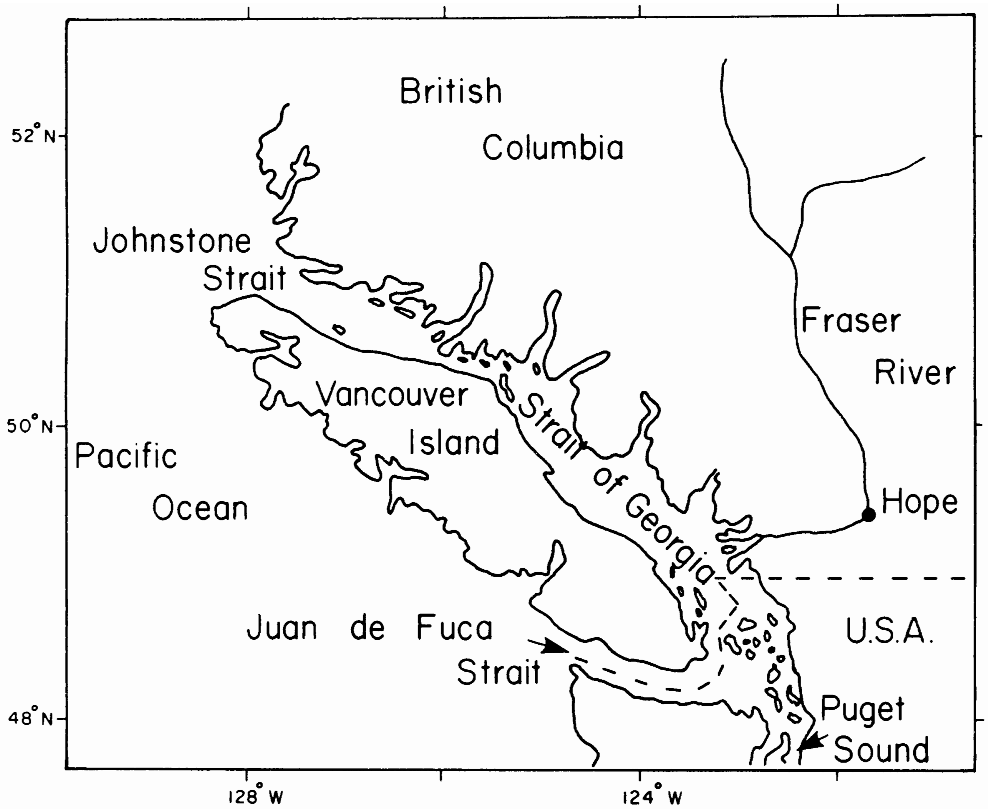


FIG. 1. Study area, showing the Strait of Georgia, lower Fraser River, and other locations mentioned in the text.

nutrient-rich waters are eventually entrained into the surface waters (Harrison et al. 1983; St. John et al. 1992). The estuarine circulation, therefore, has a major impact on the marine food production system in the Strait of Georgia. It follows that Fraser River flows must be considered to be linked to the marine food production system in the Strait of Georgia. Assuming that the early marine mortality of salmon is directly or indirectly related to the availability of food, the flow from the Fraser River could be associated with the marine mortality of salmon. Because most marine mortality of salmon occurs shortly after the smolts enter salt water (Parker 1968; Bax 1983), there might be a relationship between Fraser River flows and salmon year-class strength (termed brood year when referring to salmon).

The highest recorded discharge from the Fraser River was in 1976, followed by a very low discharge in 1977. In 1977, chinook and coho salmon entering the Strait of Georgia had exceptionally high survival resulting in large catches from these year classes (Beamish 1993). The exceptional production in 1977 lead to our hypothesis that the pattern of Fraser River discharge might be related to trends in fish production within the strait.

In this study, we examined the interannual relationships between annual changes in Pacific salmon and Pacific herring (*Clupea pallasi*) production and annual changes in Fraser River discharge. We compared annual discharge with annual fish production using the data series and residuals from smoothed trends in these series. There was no apparent relationship between discharge and long-term abundance trends except for one coho catch data series. We have not included these results in this report because the examination of long-term trends in abundance is confounded by the additions of hatchery-reared salmon and regulation changes. We expect to be able to report on the relationship between long-term abundance trends and annual discharge trends in a separate publication. In this paper we focus on the interannual relationship between discharge change and indices of fish productivity changes. We included five salmon species because they all spend time in the Strait of Georgia, but we expected that a relationship would be most evident for chinook and coho because they spend more time in the strait than the other species. We included herring because earlier studies (Stocker et al. 1985) identified Fraser River discharge as one environmental variable that was associated with year-class strength.

Data and Methods

Data Analysis

We compared change in Fraser River discharge rate with our indices of abundance or survival for Pacific salmon and herring. We looked at production anomalies over short intervals to minimize the impact of factors such as regulation changes or natural changes in the ecosystem that changed the relativity of values in the time series. To test the hypothesis that there was no relationship between anomalous discharge rate and fish production in the Strait of Georgia, we initially looked at anomalies to a 2-yr average for each value in the fish production and discharge data series. We observed that a 2-yr anomaly provided a good estimate of years of extreme change in discharge. However, for the fish production time series, anomalies to a 3-yr average are more representative of positive or negative changes in production. So, for this paper, we used both 2- and 3-yr anomalies.

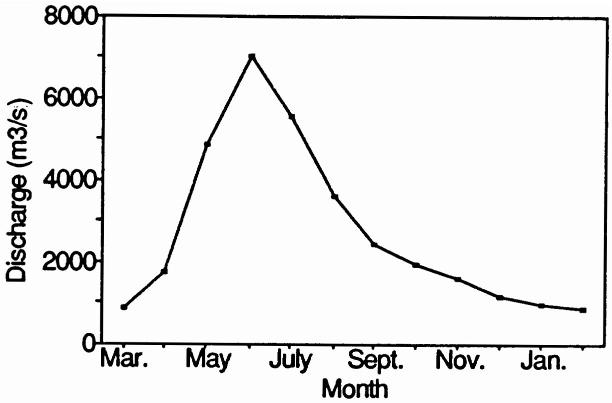


FIG. 2. Average daily discharge rate of the Fraser River averaged for each month from 1960 to 1992. March is the month with the lowest average daily discharge and June has the highest discharge. Discharge reaches a maximum quickly during May and June.

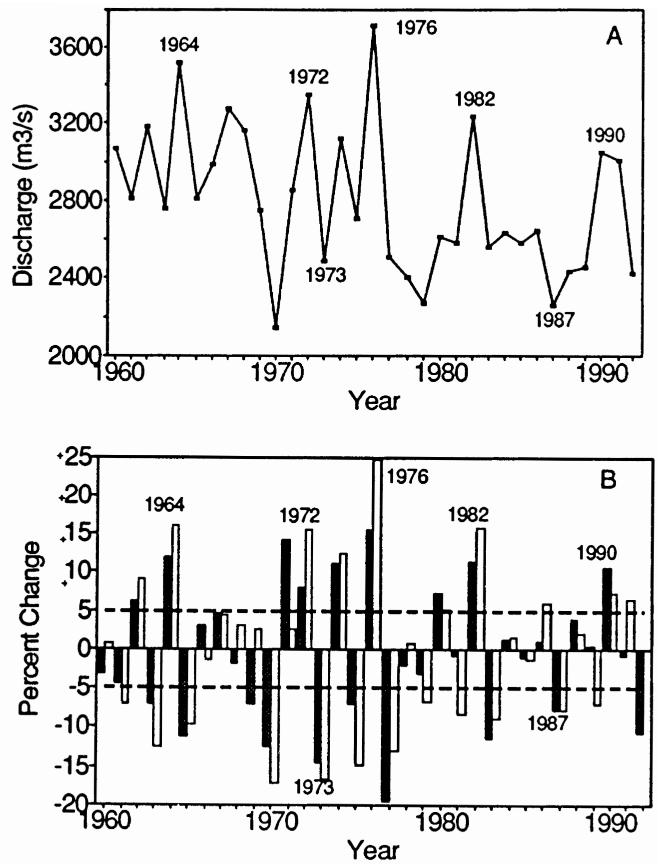


FIG. 3. (A) Annual average daily discharge rate from 1960 to 1992 showing the variation in annual discharge. For reference, some of the extreme years in discharge are identified. The highest average daily discharge rate occurred in 1976. Note that the pattern of discharge changes and appears to decline after 1976. (B) Changes in discharge expressed as a percent change from the previous year (2-yr changes) and previous and following years (3-yr changes). Years of anomalous high discharge were chosen to be those years greater than 5%; years of anomalous low discharge were those less than 5% (broken lines). The shaded bars represent the 2-yr changes and the open bars the 3-yr changes.

The fish production time series were selected based on their availability, length, and because there was a reasonable probability that the series represented an index of year-class abundance or survival. Our indices of abundance may not be directly proportional to changes in population size, but we speculated that an increase or a decrease in abundance of salmon would be reflected in the catches in unregulated fisheries or in quota revisions in regulated fisheries. We expected that some errors and approximations were present in the time series, but these were likely to occur in only a short portion of the series. Because the time series were relatively long, we expected that an association of natural, interannual abundance changes with interannual changes in discharge might be apparent despite some errors in the data series. All abundance indices were lagged to match the year salmon entered the Strait of Georgia or the year herring spawned. Except for Pacific herring, chum salmon, and the hatchery survival data series for chinook and coho salmon, we started our time series in 1960 when recreational fishing data for coho were first available. Data were available for some fisheries a few years earlier, but to minimize data errors associated with some of the early data, and to ensure that we compared discharge and production over a long enough period, we chose to start all salmon data series in 1960. The Pacific herring abundance index started in 1975, chum salmon abundance estimates in 1965, and the hatchery survival data in 1973, as will be explained subsequently.

We calculated the 2- and 3-yr anomalies in each time series by comparing values in one year (1) with the average of that year and the preceding year and (2) with the average of the one year and the preceding and following years and expressing this difference as a percentage of the 2- or 3-yr average as follows:

$$(1)\quad Z_i = \left(X_i \left(\sum_{j=-1}^{0} X_{i+j} / 2 \right) \right) \Big/ \left(\sum_{j=-1}^{0} X_{i+j} / 2 \right) \times 100$$

$$(2)\quad Z_i = \left(X_i \left(\sum_{j=-1}^{1} X_{i+j} / 3 \right) \right) \Big/ \left(\sum_{j=-1}^{1} X_{i+j} / 3 \right) \times 100$$

where Z_i = is the percent change in year i and X_t is the value in the current year. Depending on the data series, we chose a value of above or below between a 5 and 20% change as an extreme anomaly.

We tested the hypothesis that there was no relationship between changes in Fraser River discharge and the production anomalies using a chi-square (χ^2) test (Press et al. 1986). Each chi-square table compared anomalies of high discharge and poor production, average discharge and poor production, low discharge and poor production, high discharge and good production, average discharge and good production, and low discharge and good production. We excluded years of average fish production because we were comparing anomalous fish production with Fraser River discharge.

Fraser River Discharge

Freshwater discharge from the Fraser River results mostly from snow melting in the mountains in the drainage area. Most melting occurs in the spring (Moore 1991), resulting in a pattern of annual discharge that is low early in the year and reaches a maximum in June (Fig. 2). The discharge rate is measured daily at Hope (Fig. 1) and measurements were

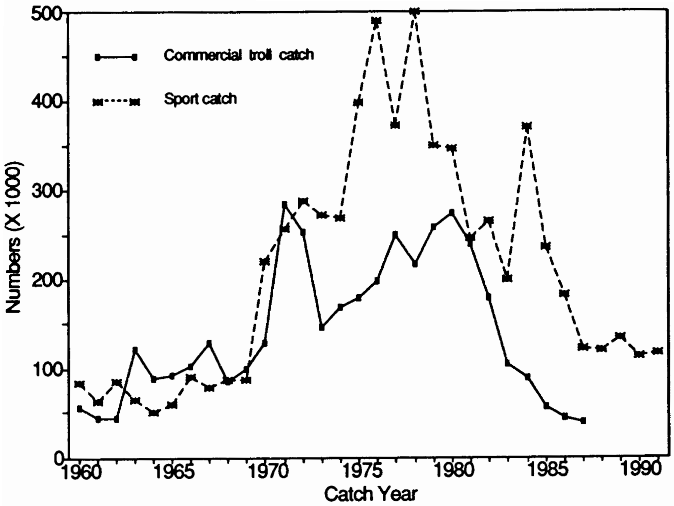


FIG. 4. Number of chinook salmon caught in the commercial troll and sport fisheries in the Strait of Georgia. In the early 1970s, the sport catch increased and exceeded the commercial troll catch, but the general trends in abundance were similar. In the 1980s, catches in both fisheries declined.

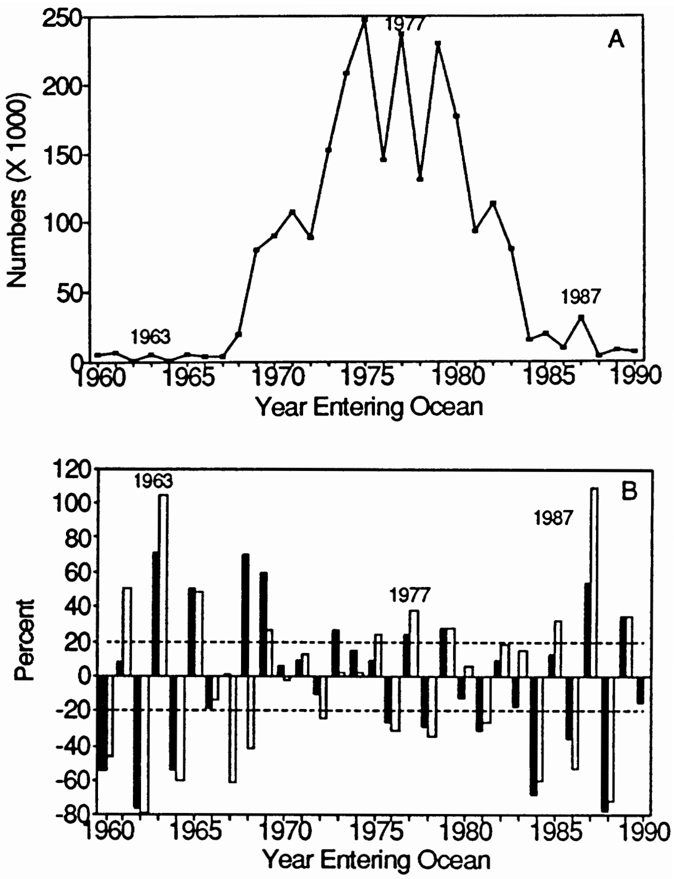


FIG. 5. (A) Two-year-old index of chinook salmon caught in the Strait of Georgia sport fishery. The numbers are related to the year that the smolts entered the ocean. (B) The data in Fig. 5A expressed as a percent change. Years of anamalous good production were greater than 20%; years of anomalous low production were less than 20% (broken lines). The shaded bars represent the 2-yr changes and the open bars the 3-yr changes.

published by Environment Canada (1990). We used an average of the 12 average monthly discharge rates as an index of average annual discharge. We used the 12-mo period between April 1 and March 31 of the following year. This provided an index of the total discharge between the lowest values in the annual cycle (Fig. 3A).

Chinook Salmon

Chinook salmon that enter the Strait of Georgia are produced in approximately 75 rivers that flow directly or indirectly into the strait (Argue et al. 1983) and in almost 20 Canadian hatcheries. Most chinook salmon spawn in the fall and their progeny enter salt water in the late spring of the following year. In general, chinook salmon return to spawn in their natal streams between their second and fifth year of ocean life (Healey 1991). During the period of ocean residence, chinook salmon originating from rivers and hatcheries around the Strait of Georgia may remain in the strait or may move offshore. The commercial and sport fisheries in the strait catch chinook produced from rivers and hatcheries around the strait, as well as chinook produced in rivers and hatcheries in Puget Sound in the United States (Argue et al. 1983). The commercial and sport catch of chinook salmon is available through the Department of Fisheries and Oceans data bases (Kuhn et al. 1988; Holmes and Whitfield 1991).

Chinook salmon from any particular brood year can appear in the catch over a number of years, and it has been shown that the relative abundance of the age-2 fish (i.e., 2 yr after spawning or one winter annulus) is indicative of the relative survival of chinook salmon produced in hatcheries (Fraser et al. 1983). Thus, it is possible that the abundance of age-2 fish is also an index of year-class strength. We used catch and age composition data to calculate an index that reflected the abundance of age-2 fish.

The trends in the catch of chinook in the commercial and sport fisheries were similar over the time series, except, beginning in the mid-1970s, sport catches exceeded commercial catches (Fig. 4). Before 1983, estimates of age composition in the sport fishery were not available, but estimates of the catch of age-2 or "jack" chinook salmon in the commercial fisheries were (B.E. Riddell, Pacific Biological Station, Department of Fisheries and Oceans, Nanaimo, B.C., personal communication). We used the proportion of "jack" chinook salmon in the commercial fishery as an index of the percentage of age-2 chinook in the sport fishery for the period 1960–1982. For the period 1983–1990, the estimated proportion of age-2 chinook in the sport fishery was taken from the age composition estimates of fish from the sport creel survey (Collicutt and Shardlow 1992). The age-2 index, therefore, approximates the percentage of age-2 fish caught in the sport fishery and is expressed as numbers of chinook caught (Fig. 5A). Due to the potential differences in exploitation patterns and regulatory mechanisms between the sport and commercial fisheries and changes within the fisheries themselves, the commercial data may not accurately estimate the proportion of age-2 fish caught in the sport fishery. However, in using the calculated index, we assumed that the catches from both fisheries will reflect large interannual changes in the abundance of age-2 chinook and that our index may capture these changes.

We also used the total catch of chinook in the sport fishery in the strait as an index of year-class strength. The sport fishery operates throughout the year, and until increased size limits were introduced beginning in 1981, a strong chinook

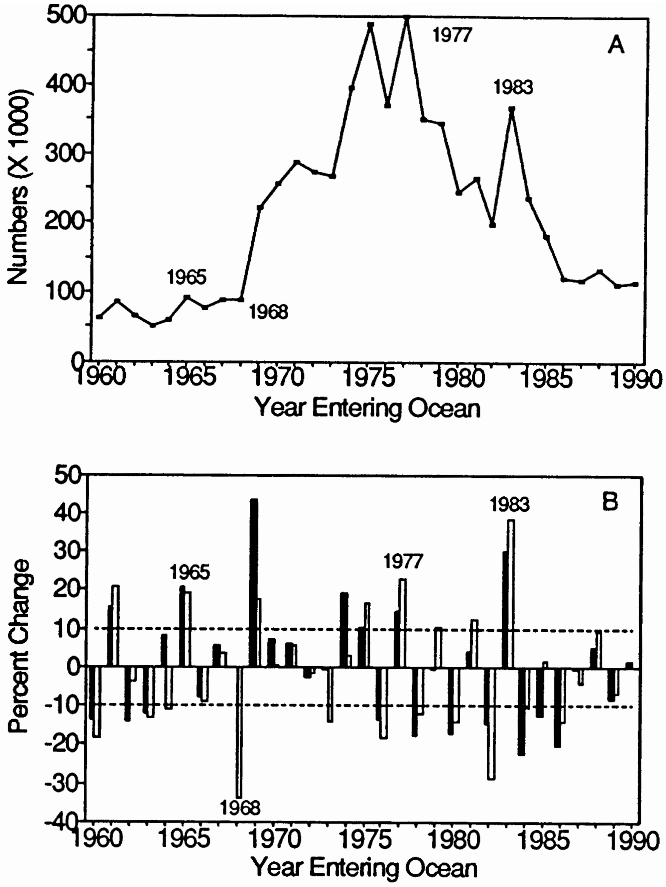


FIG. 6. (A) Number of chinook salmon caught in the Strait of Georgia sport fishery. The numbers are related to the year that the smolts entered the ocean. (B) The data in Fig. 6A expressed as a percent change. Years of anomalous good production were greater than 10%; years of anomalous low production were less than 10% (broken lines). The shaded bars represent the 2-yr changes and the open bars the 3-yr changes.

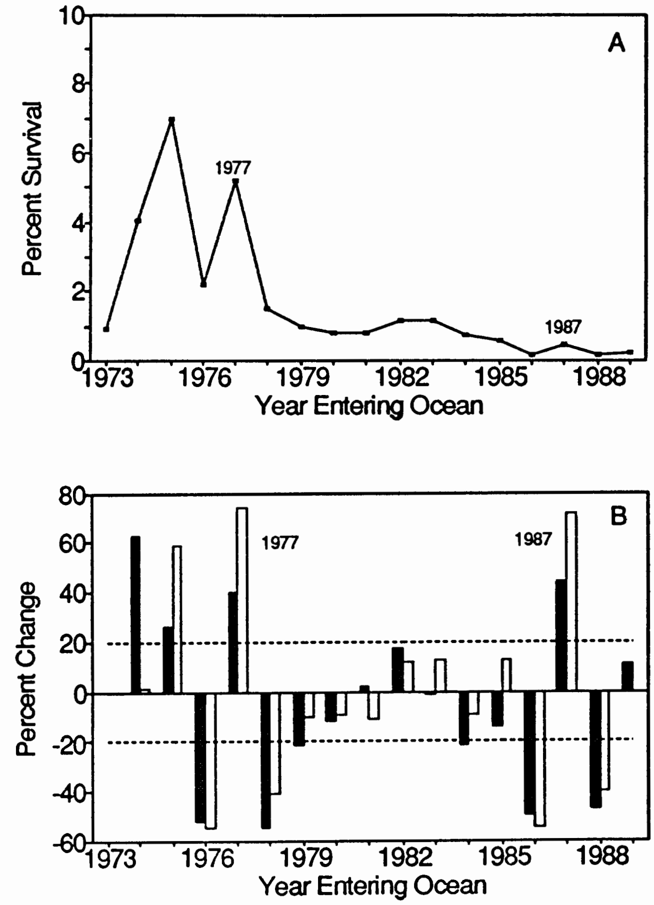


FIG. 7. (A) Percent survival of chinook salmon produced in hatcheries in the Strait of Georgia and the Fraser River. Percent survival for each brood year is related to the year that the brood year entered the ocean. Over the time series, hatchery survival trends increased and then decreased. (B) The data in Fig. 7A expressed as a percent change. Years of anomalous good production were greater than 20%; years of anomalous low production were less than 20% (broken lines). The shaded bars represent the 2-yr changes and the open bars the 3-yr changes.

year class would be expected to be identifiable in the catch in its second marine year (Fig. 6A). We did not expect the total sport catch to be as representative of brood-year strength as the age-2 index, because the chinook caught in the fishery were from multiple age classes. Nevertheless, it was possible that above or below-average brood-year strength might be detectable in the sport catch. For this analysis, we assumed that the fish were caught at age 3.

The third data series used to represent chinook production was the percent survival of chinook salmon from hatcheries (Fig. 7A). Hatchery survival estimates, based on returns of salmon marked with coded-wire tags, were available from 1973 until the most recent complete brood-year returns in 1988 (Kuhn et al. 1988).

Coho Salmon

Coho salmon are common in many of the streams and rivers that flow into the strait (Argue et al. 1983) and are reared in approximately 20 Canadian hatcheries. Coho salmon spawn in fresh water in the fall and the eggs hatch in the following spring. Most young coho spend 1 yr in fresh water before entering the ocean (Sandercock 1991). During the period of ocean residence, coho may remain in the strait or they may move offshore. Most coho salmon return to their natal streams in their second year of ocean life (Sandercock 1991).

The commercial and sport catches of coho salmon in the Strait of Georgia are available through the records of the Department of Fisheries and Oceans (Holmes and Whitfield 1991; Collicutt and Shardlow 1992). Beginning in the late 1960s, the sport catch of coho greatly exceeded the commercial catch, but the trends in catch were similar (Fig. 8, 9A, 10A). Because the coho catch is virtually from one brood year, we used data bases from both the sport and commercial fisheries as an index of production.

The third coho salmon data series was the percent survival of hatchery-reared coho beginning in 1973 (Fig. 11A). In the 1970s and 1980s, hatcheries located around the Strait of Georgia produced coho that were released into the strait. Estimates of the numbers of smolts released by hatcheries into the Strait of Georgia and the Fraser River and the return of adults from these releases were used to calculate hatchery survival (Kuhn et al. 1988).

Pink, Chum, and Sockeye Salmon

Pink, chum, and sockeye salmon produced in the Fraser River are thought to reside in the strait for only a few months. We used salmon production data from the Fraser

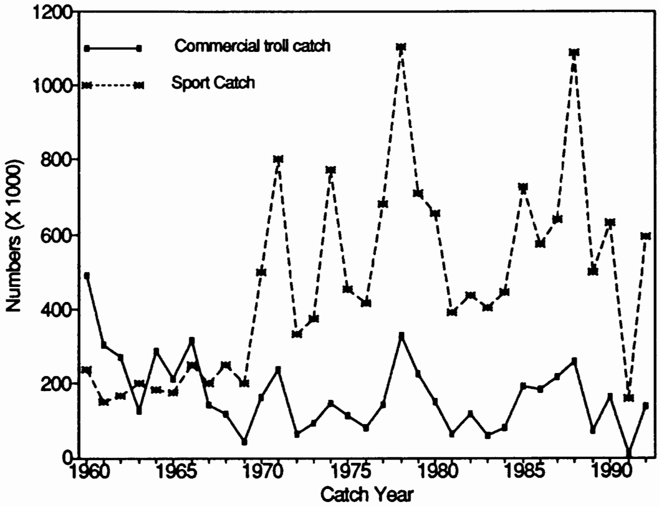
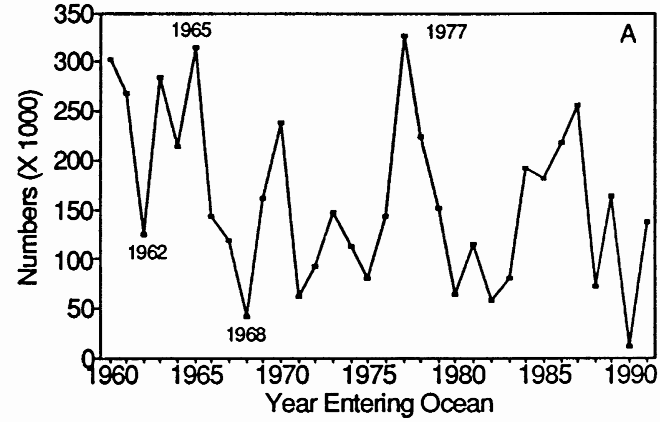


FIG. 8. Number of coho salmon caught in the commercial troll and sport fisheries in the Strait of Georgia. Beginning in the early 1970s, the sport catch exceeded the commercial troll catch. The total catch in the sport fishery fluctuated as a result of changes in effort and fish abundance but not as a result of direct quota regulation. In 1991, the coho catch in both fisheries declined dramatically and was the lowest in the data series.



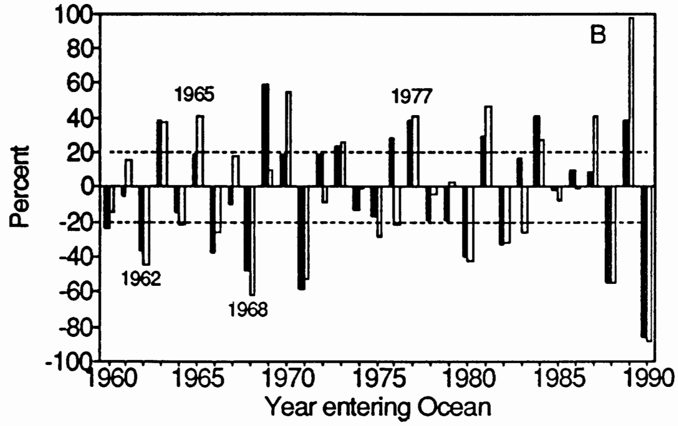


FIG. 9. (A) Number of coho salmon caught in the commercial troll fishery in the Strait of Georgia. The numbers are related to the year that the smolts entered the ocean. Catch year would be 1 yr later and brood year would be 2 yr earlier. The catch in 1978 of coho entering the ocean in 1977 is the highest in the time series. (B) The data in Fig. 9A expressed as a percent change. Years of anomalous good production were greater than 20%; years of anomalous low production were less than 20% (broken lines). The shaded bars represent the 2-yr changes and the open bars the 3-yr changes.

River because virtually all of the pink and sockeye salmon and many of the chum salmon that move through the strait are from the Fraser River (Healey 1980).

Chum salmon spawn in the fall and the eggs hatch in the following spring. Chum salmon from the Fraser River move into the Strait of Georgia from April to May (Healey 1980). They are reported to remain in the strait until July, when they migrate into the northern North Pacific Ocean (Healey 1980). We determined brood-year strength for chum salmon by partitioning estimates of the annual catch and escapement for Fraser River stocks, available for the period 1965–1987 (Beacham and Starr 1982; M. Joyce, Fraser River Division, Department of Fisheries and Oceans, personal communication), into age groups using the percentage age composition (age 2 = 28.1%, age 3 = 61.4%, age 4 = 10.5%) determined by Beacham and Murray (1987). We then assigned the appropriate catch and escapement to the appropriate brood year to produce an index of brood-year strength (Fig. 12A) that was then used to identify high and low years of production and test significance as was done for the other salmon (Fig. 12B).

Pink salmon spawn in the fall, and the fry that hatch in the following spring begin their downstream migration immediately after emerging from the gravel (Neave 1966). The young pink salmon migrate into the strait during March and April, and by July, virtually all pink salmon have left the strait (Healey 1980). Almost all pink salmon from the Fraser River spawn in odd-numbered years and the fry enter the Strait of Georgia in even-numbered years (Neave 1966). We used estimates of catch and escapement produced by the Pacific Salmon Commission (PSC 1990) as an index of brood-year strength (Fig 13A).

Sockeye salmon in the Fraser River spawn in the fall, and the fry that emerge from the gravel early in the year move into lakes where most remain for 1 yr before going to sea as smolts. The smolts move into the Strait of Georgia toward the last 2 wk of April, and by the end of May, most have left the strait (Groot and Cooke 1987). The sockeye smolts move northward, remaining in the strait for about 1 mo. This is the shortest period of residence in the strait of any of the five species of Pacific salmon. Almost all (90%) of the sockeye salmon from the Fraser River spend 2 yr in the ocean before they return to spawn (Vernon 1982).

Most of the stocks of sockeye salmon from the Fraser River are characterized by 4-yr cyclic abundance changes (Fig. 14A). The largest of the lines or years that make up a cycle is dominated by the Adams River stock that returned to spawn in 1982, 1986, 1990, etc. There is no consensus about the mechanism responsible for the cycles, but their existence requires that production from each of the four years in the cycle be compared separately. Catch and escapement data were obtained from the Pacific Salmon Commission (PSC 1986–1989) and International Pacific Salmon Fisheries Commission (IPSFC 1965–1985) and separated into the 4-yr cycles (Fig. 14A). Within each cycle, the relative production of each year or line was compared with the same line in the previous cycle (Fig. 14B).

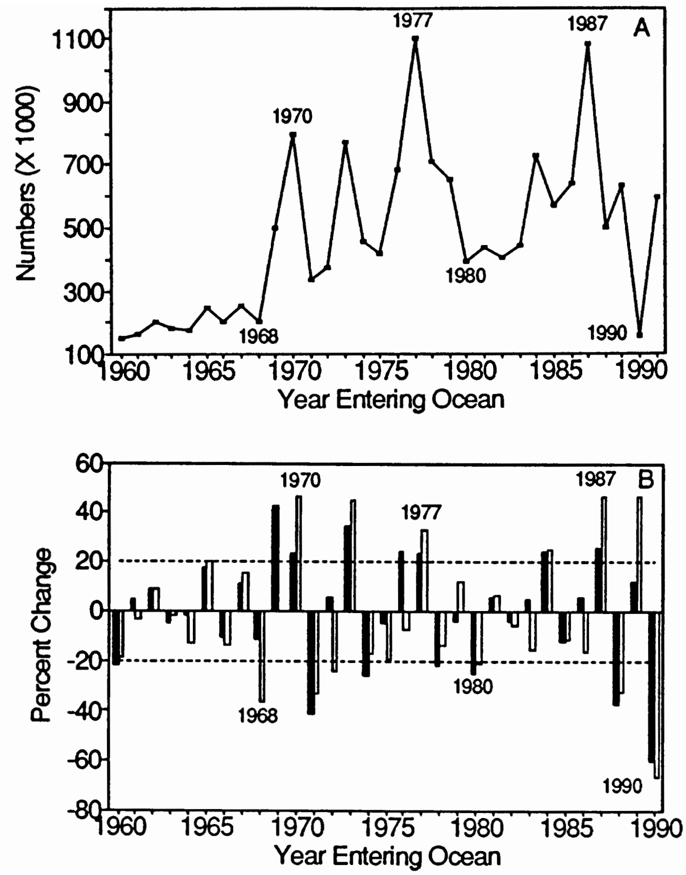


FIG. 10. (A) Number of coho salmon caught in the sport fishery in the Strait of Georgia. The numbers are related to the year that the smolts entered the ocean. Catch year would be 1 yr later and brood year would be 2 yr earlier. Note in this figure and in Fig. 9 the very low catch in 1991 of coho that went to sea in 1990 and the high catch in 1978 of coho that went to sea in 1977. (B) The data in Fig. 10A expressed as a percent change. Years of anomalous good production were greater than 20%; years of anomalous low production were less than 20% (broken lines). The shaded bars represent the 2-yr changes and the open bars the 3-yr changes.

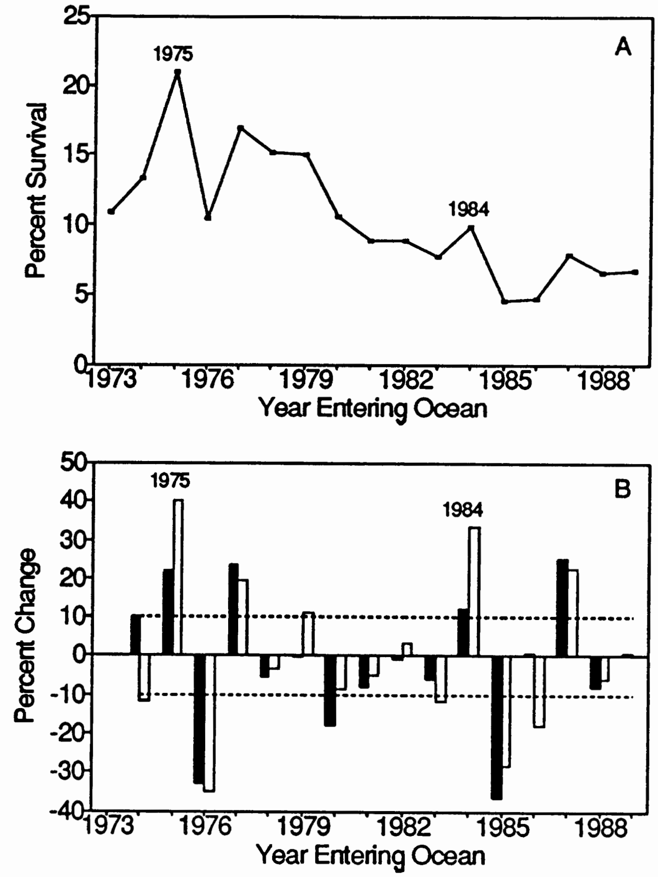


FIG. 11. (A) Percent survival of coho salmon produced in hatcheries in the Strait of Georgia and the Fraser River. Percent survival for each brood year is related to the year that the brood year entered the ocean. There is a declining trend in survival, but an increasing number of smolts were released until the mid-1980s (Cross et al. 1991). There is not as much interannual variation as occurred in the catch data. (B) The data in Fig. 11A expressed as a percent change. Years of anomalous good production were greater than 10%; years of anomalous low production were less than 10% (broken lines). The shaded bars represent the 2-yr changes and the open bars the 3-yr changes.

Pacific Herring

Pacific herring stocks in the Strait of Georgia provide food for salmon and other predators, as well as sustaining an important commercial fishery. There is a small resident population and a larger migratory population that moves into the strait in the fall and spawns in the following winter (Hourston and Haegele 1980). The juvenile herring remain in the strait for over a year, migrating offshore in the following summer.

The Pacific herring fishery was the largest fishery in British Columbia from the late 1940s to the mid-1960s with catches in the 1950s and 1960s of approximately 200 000 t (Hourston and Haegele 1980). However, the large catches of the early 1960s (up to 260 000 t) could not be sustained and the fishery was shut down in 1968. The fishery started again in 1971 as a roe fishery and currently harvests about 35 000 to 40 000 t. An index of the age-2+ biomass has been produced starting in 1952 (Schweigert et al. 1993), but because of sampling problems in the late 1960s and early 1970s associated with the closure of the fishery, the reconstructions of year classes for this period may only approximate the actual population structure (V. Haist, Department of Fisheries and Oceans, Pacific Biological Station, Nanaimo, B.C., personal communication) Thus, we arbitrarily started our data series in 1975 (Fig. 15A). We identified strong and weak year classes using the age-2+ biomass in Schweigert et al. (1993) for all Strait of Georgia Pacific herring stocks (Fig. 15B).

Results

Fraser River Discharge

We selected discharge anomalies above and below the 5% level as years of above- and below-average discharge, respectively (Fig. 3B). The years in between were considered to be years of average discharge. Years of change to very high and very low discharge were identified using both the 2- and 3-yr anomalies described earlier. Both procedures identified anomalies, but because of the particular pattern of discharge, the 2-yr anomaly index appears to identify years of change slightly better than the 3-yr index that identified a slightly higher number of anomalous years. For

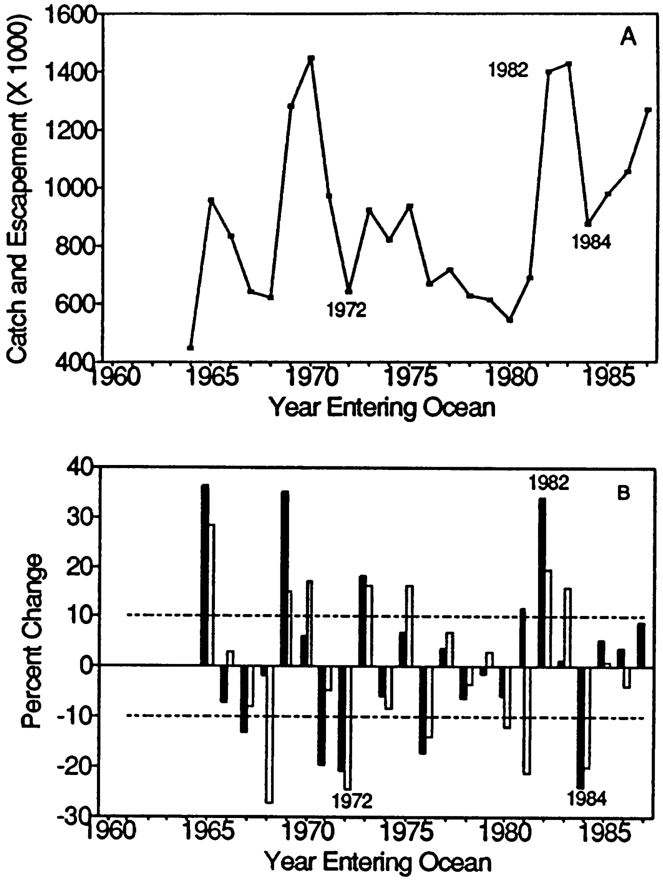


FIG. 12. (A) Catch and escapement of chum salmon produced in the Fraser River. The numbers are related to the year that the smolts entered the ocean. The catch year would be 2 yr later and the brood year would be 1 yr earlier. (B) The data in Fig. 12A expressed as a percent change. Years of anomalous good production were greater than 10%; years of anomalous low production were less than 10% (broken lines). The shaded bars represent the 2-yr changes and the open bars the 3-yr changes.

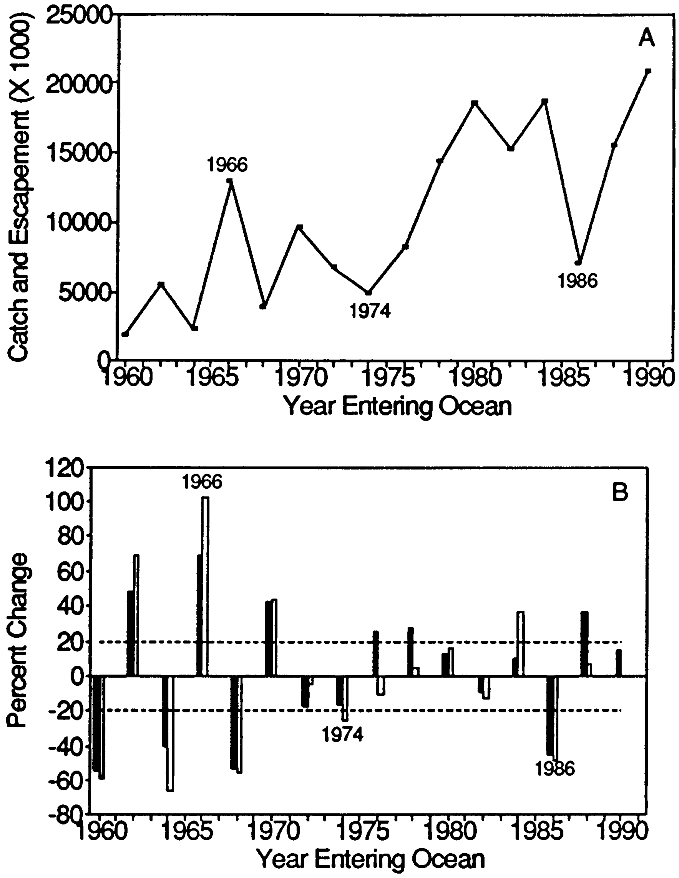


FIG. 13. (A) Catch and escapement of pink salmon produced in the Fraser River. The numbers are related to the year that the smolts entered the ocean. (B) The data in Fig. 13A expressed as a percent change. Years of anomalous good production were greater than 20%; years of anomnalous low production were less than 20% (broken lines). The shaded bars represent the 2-yr changes and the open bars the 3-yr changes.

example, the 3-yr index identifies 1989 as a year of extremely low average discharge whereas this year is not anomalous in the 2-yr index. There is a change in discharge from 1986 to 1987 resulting in 1987 being identified as a low-discharge year and from 1989 to 1990 resulting in 1990 being a high-discharge year (Fig. 3), but 1989 is not a year of extreme change to either high or low discharge.

Despite some differences, both indices identified most of the same years as discharge anomalies. From 1960 to 1992, there were nine years identified as having extremely high discharge using the 2-yr index and 10 using the 3-yr index; seven years were the same for both indices. Similarly, there were 10 years identified as extremely low discharge using the 2-yr index and 12 using the 3-yr index; eight years were the same for both indices.

Chinook Salmon

We identified years of anomalously low and high production as values that exceeded 20% except for the sport catch where we used a 10% level. The 2-yr index of chinook age-2 abundance indicated that there were 18 of 30 years of anomalously high (9) or low (9) production (Fig. 5B). For the sport catch, 17 of the 30 years in the time series were identified as years of high (7) or low (10) production (Fig. 6B). Ten of 15 years were identified as having relatively high (4) or low (6) values in the hatchery survival data (Fig. 7B).

The 3-yr index of age-2 chinook abundance indicated that there were 22 of 30 years of anomalously high (10) or low (12) production (Fig. 5B). The 3-yr index of the sport catch indicated that 19 of 30 years were anomalously high (8) or low (11) (Fig. 6B) For hatchery survival, seven out of 15 years were anomalously high (3) or low (4) (Fig. 7B).

All of the chinook production anomaly indices were closely related to the pattern of Fraser River discharge (χ^2 test, $P <$ 0.05 or 0.01) (Table 1). For all data series, anomalously high production of chinook salmon in the Strait of Georgia corresponded closely to the years of anomalously low Fraser River discharge, and anomalously low production of chinook corresponded closely to years of anomalously high Fraser River discharge. In the 2-yr index, only one of 25 anomalous years of low production occurred during an extreme change to low discharge and only two of 20 years of anomalously high production occurred during an extreme change to high discharge (Table 2). The 3-yr index comparisons were similar to the 2-yr index comparisons (Table 2). There were no years of very high production in years of

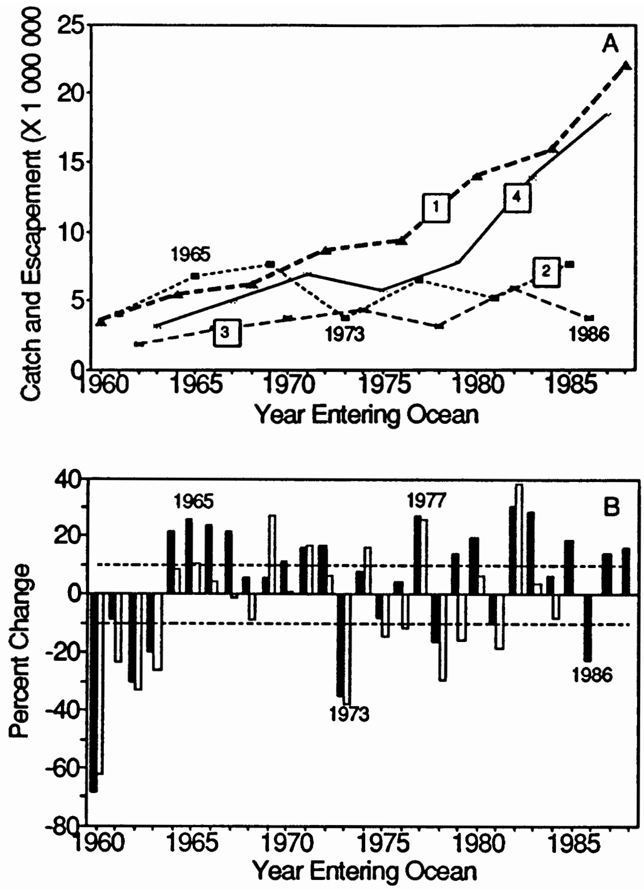


FIG. 14. (A) Catch and escapement of sockeye salmon produced in the Fraser River. The numbers are related to the year that the smolts entered the ocean. The catch year would be 2 yr later and the brood year would be 2 yr earlier. In general, there was not as much variation for sockeye as found for the catches of other salmon. There was a trend of rapidly increasing abundance beginning in the late-1970s in two of the lines. The 4-yr cycles are shown separately (labelled 1–4 consecutively). The strongest cycle is (1): the 4-yr cycle beginning in 1960. (B) The data in Fig. 14A expressed as a percent change. Years of anomalous good production were greater than 10%; years of anomalous low production were less than 10% (broken lines). The shaded bars represent the 2-yr changes and the empty bars the 3-yr changes.

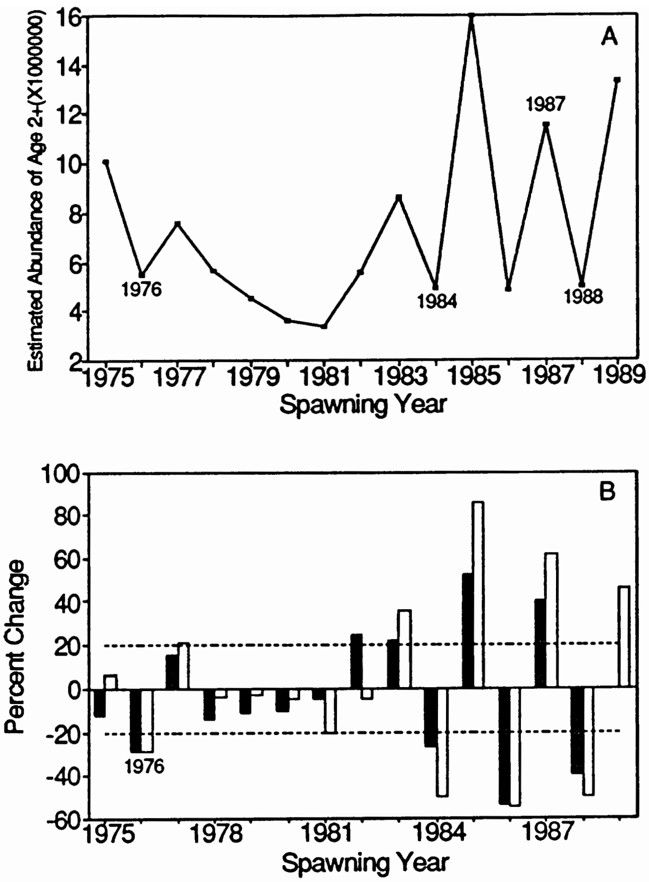


FIG. 15. (A) Estimated abundance of age-2+ herring in the Strait of Georgia. (B) The data in Fig. 15A expressed as a percent change. Years of anomalous good production were greater than 20%; years of anomalous low production were less than 20% (broken lines). The shaded bars represent the 2-yr changes and the open bars the 3-yr changes.

extreme increases in discharge, and only three of 27 years had very low production when discharge changed to a very low level (Table 2).

Coho Salmon

We identified years of anomalously high and low production as values that exceeded ±20% except for hatchery survival estimates where we used ±10% because the variations in the data were not as large as in the other series. Using the 2-yr index for the commercial catch anomalies, there were 17 of 31 years of either anomalously high (8) or low (9) commercial catches (Fig. 9B). In the 2-yr index of coho sport catch anomalies, 14 of 31 yr were anomalously high (7) or low (7) (Fig. 10B). In the 2-yr index of coho hatchery survival anomalies, seven out of 15 years were anomalously high (4) or low (3) (Fig. 11B).

The 3-yr index produced about the same number of anomalies in production. In the commercial catch, there were 21 of 31 years of either anomalously high (9) or low (12) catches (Fig. 9B). In the 3-yr index of coho sport catch, 12 of 31 years were high (6) or low (6) sport catches (Fig. 10B). In the 3-yr index of coho hatchery survival, nine out of 15 years were high (5) or low (4) (Fig. 11B).

All of the coho production anomaly indices were closely associated with the pattern of Fraser River discharge (χ^2 test, $P < 0.05$ or 0.01) except for the 2-yr index of hatchery survival (χ^2 test, $P < 0.25$) (Table 3). For the 2-yr indices, none of the 19 years of change to very low production occurred when discharge changed from very high to very low levels (Table 4). Only two of 19 years of above-average production occurred when discharge changed from very low to very high levels (Table 4). For the 3-yr indices, the results were very similar (Table 4). There were no years of very high production anomalies occurring in years with large increases in discharge and only two of 22 years of very low production when large declines in discharge occurred.

Chum Salmon

Percent differences greater than 10% were considered to represent years of anomalously high or low production. For the 2-yr index of extreme chum production, there were 11 of 23 years of anomalously high (6) and low (5) chum salmon production (Fig. 12B), and for the 3-yr indices, there were

TABLE 1. Relationship among the two Fraser River discharge anomaly indices and the 2- and 3-yr anomalies of chinook salmon production. Chi-square (χ^2) values are shown for each possible relationship and significance levels are indicated as $**P < 0.05$, $***P < 0.01$.

Fraser River discharge anomaly index	Age-2 abundance index		Sport catch		Hatchery survival	
	2-yr	3-yr	2-yr	3-yr	2-yr	3-yr
2-yr	10.00***		6.83**		7.88**	
3-yr		12.35***		9.28***		7.1**

TABLE 2. Numbers of extreme production anomalies of chinook salmon in relation to Fraser River discharge anomalies.

	Fraser River discharge anomaly					
	2-yr			3-yr		
Production anomaly	Very low	Average	Very high	Very low	Average	Very high
Very high	14	4	2	18	3	0
Very low	1	16	8	3	12	12

13 of 22 years of anomalously high (7) and low (6) chum salmon production (Fig. 12B). High chum salmon production anomalies rarely occurred in years of anomalously high discharge, and low chum salmon production anomalies rarely occurred in years of anomalously low discharge (Table 5). However, for neither the 2- nor the 3-yr chum salmon production indices was the relationship with discharge and anomalous production as close as was observed for chinook and coho salmon. A comparison of the 2-yr indices did indicate a weak relationship (χ^2 test, $P < 0.10$), but the comparison of the 3-yr indices did not reject the hypothesis that there was no relationship between anomalous production and discharge (χ^2 test, $P < 0.25$) (Table 6).

Pink Salmon

Anomalies greater than ±20% were chosen to represent years of anomalously high or low production. We were unable to reject the null hypothesis that there was no relationship between anomalous production of pink salmon and anomalous Fraser River discharge (Table 7). For the 2-yr index, 10 of 16 years had anomalously high (6) or low (4) pink salmon production (Fig. 13B). Using the 3-yr index, there were again 10 of 16 years of high (5) or low (5) production relative to the previous pink salmon production year (Fig. 13B). However, the hypothesis of no relationship between discharge and production anomalies was supported (χ^2 test, $P > 0.25$) (Table 7).

Sockeye Salmon

Anomalies greater than ±10% were chosen to be extreme for sockeye salmon. Production anomalies identified for each of the lines in a 4-yr cycle were combined into one data series to be compared with the discharge anomalies. Using the 2-yr index, there were 22 of 29 years of high (15) or low (7) sockeye production (Fig. 14B). Using the 3-yr index, there were 16 of 25 years of high (6) or low (10) sockeye production (Fig. 14B). There was no indication of a close relationship between discharge and production for either the 2- or 3-yr indices (Table 8).

Pacific Herring

Anomalies greater than ±20% were chosen to be extreme for Pacific herring. According to our 2-yr index, there were eight of 14 years of high (4) or low (4) Pacific herring production (Fig. 15B). In the 3-yr index, there were nine out of 14 yr of high (4) or low (5) herring production (Fig. 15B). The analysis of anomalous production of Pacific herring did not, in general, support the hypothesis of a close relationship between extreme anomalies in discharge and production (Table 9).

Discussion

Our study showed that the extreme Fraser River discharge anomalies are closely related to extreme year-to-year anomalies in the abundance and survival indices of chinook and coho salmon and probably less closely associated with chum salmon. In all of the observations for chinook and coho salmon, using all of the data series, large increases in catch or survival relative to the previous year rarely occurred for brood years that went to sea when there was a large increase in Fraser River discharge levels relative to the previous year. Similarly, large decreases in catch or survival relative to the previous year almost never occurred for brood years that went to sea in years when there was a large decrease in Fraser River discharge levels relative to the previous year. There was no indication of a close relationship between discharge anomalies and pink and sockeye salmon and Pacific herring production anomalies. The fact that it was possible to demonstrate a close relationship between discharge and chinook and coho production, despite the potentially confounding effects of fishing effort, escapement levels, freshwater habitat conditions, and potential data errors, clearly demonstrates that the pattern of Fraser River discharge affects the early marine survival of chinook and coho in the Strait of Georgia.

The method of identifying extreme anomalies had little effect on the acceptance or rejection of the null hypothesis for the chinook and coho abundance indices except that in some cases the level of significance was higher. The method used to select an anomaly did affect the acceptance of the relationship between extreme survival of coho reared in hatcheries and anomalous discharge. The 3-yr survival index and the 3-yr Fraser River discharge index were closely related (χ^2 test, $P < 0.05$) for coho hatchery survival anomalies, whereas a comparison using 2-yr indices was not

TABLE 3. Relationship among the two Fraser River discharge anomaly indices and the 2- and 3-yr anomalies of coho salmon production. Chi-square (χ^2) values are shown for each possible relationship and significance levels are indicated as $^{**}P < 0.05$, $^{***}P < 0.01$.

Fraser River discharge anomaly index	Commercial catch		Sport catch		Hatchery survival	
	2-yr	3-yr	2-yr	3-yr	2-yr	3-yr
2-yr	6.64***		7.8**		4.2	
3-yr		11.17***		9.0**		8.81**

TABLE 4. Numbers of extreme production anomalies of coho salmon in relation to Fraser River discharge anomalies.

	Fraser River discharge anomaly					
	2-yr			3-yr		
Production anomaly	Very low	Average	Very high	Very low	Average	Very high
Very high	12	5	2	18	2	0
Very low	0	8	11	2	9	11

TABLE 5. Numbers of extreme production anomalies of chum salmon in relation to Fraser River discharge anomalies.

	Fraser River discharge anomaly					
	2-yr			3-yr		
Production anomaly	Very low	Average	Very high	Very low	Average	Very high
Very high	4	1	1	5	1	1
Very low	0	2	3	1	2	3

related (χ^2 test, $P < 0.25$). In the case of hatchery survival data, we think that there may be a close relationship between extreme Fraser River discharge anomalies and changes in the annual survival of hatchery-reared coho but that the relationship does not appear to be as clear for hatchery survival as for the other indices. Hatchery-reared coho represent approximately 54% of the coho catch in the Strait of Georgia, 35% from Canadian hatcheries (Cross et al. 1991), and 19% from American hatcheries (R.J. Beamish and C.M. Neville, unpublished data). If catch anomalies are closely related to discharge anomalies and with hatchery-reared fish representing a large fraction of the catch, we would expect a close relationship between survival anomalies and discharge anomalies.

The selection of the anomaly index was also important for chum salmon. Only the 2-yr index of brood-year strength was weakly associated with discharge (χ^2 test, $P < 0.10$), but there was evidence of a production and discharge relationship. We interpret this to indicate that extreme discharge anomalies have an effect on chum salmon production, but the effects were not as clear or not as strong as was observed for chinook and coho from the data we used. The possibility of a relationship between chum salmon production anomalies and extreme discharge anomalies indicates that chum may reside in the Strait of Georgia longer than the 3–4 mo that was previously thought (Healey 1980).

Mechanism

A discussion of a possible mechanism is essentially an exercise in speculation; thus, we will keep our speculations brief. Assuming that most marine mortality occurs shortly after the salmon smolts enter salt water (Parker 1968; Bax 1983), fluctuating discharge could affect survival indirectly via the estuarine circulation or directly by physically affecting smolt distribution. We cannot prove that salmon smolts are not transported into areas less favourable for survival, but we favour a mechanism related to the estuarine circulation because our surveys in June and July 1990–1993 in the large plume of the Fraser River have not identified a movement of smolts out of the plume during high-discharge years (R.J. Beamish and C.M. Neville, unpublished data).

Nutrients in the bottom water in the Strait of Georgia are entrained into the surface waters as a consequence of the amount of turbulence at the interface between the bottom and surface layers (Farmer and Freeland 1983). It is the frequency of destabilization of the water column that appears to determine the level of nutrients in the surface or mixed layer. In the Strait of Georgia, there is less wind mixing of nitrate-rich deep water into the surface layer or euphotic zone during periods of high Fraser River discharge (St. John et al. 1992). Oceanographic factors other than discharge can also affect productivity (Harrison et al. 1983). Wind, light, and tides can be important but probably are less important, in general, than the amount of stability at the interface between the bottom and surface layers. In other words, there is a hierarchy of effects, as proposed by Levasseur et al. (1984) for the St. Lawrence River estuary. In periods of low discharge or decreased buoyancy of the surface layer, wind mixing would result in enhanced production. In fact, St. John et al. (1992) and Yin et al. (1995) observed that during periods of weak stratification, there was enhanced primary production after major wind events. In years of low or average discharge, wind, tides, and light should be important factors affecting the productivity of the surface layer. Our hypothesis is that the change to high discharge results in reduced availability of food for salmon which in turn increases the risk of predation as young salmon search for food. The opposite would occur during a change to low discharge.

Management Implications

This study and others (Drinkwater 1988) show that large sources of freshwater discharge can affect the survival of organisms in salt water. Fluctuations in total annual discharge are a common feature of the pattern of flow of the Fraser River. Records of this pattern go back to 1912 and

TABLE 6. Relationship among the two Fraser River discharge anomaly indices and the 2- and 3-yr anomalies of chum salmon abundance. Chi-square (χ^2) values are shown for each relationship and significance levels are indicated as $*P < 0.10$.

Fraser River discharge anomaly index	Fraser River production	
	2-yr	3-yr
2-yr	5.21*	
3-yr		4.11

TABLE 7. Relationship among the two Fraser River discharge anomaly indices and the 2- and 3-yr anomalies of pink salmon abundance. Chi-square (χ^2) values are shown for each relationship. None of the values were significant ($P < 0.10$).

Fraser River discharge anomaly index	Fraser River production	
	2-yr	3-yr
2-yr	1.48	
3-yr		1.2

TABLE 8. Relationship among the two Fraser River discharge anomaly indices and the 2- and 3-yr anomalies of sockeye salmon abundance. Chi-square (χ^2) values are shown for each relationship. None of the values were significant ($P < 0.10$).

Fraser River discharge anomaly index	Fraser River production	
	2-yr	3-yr
2-yr	1.28	
3-yr		1.07

TABLE 9. Relationship among the two Fraser River discharge anomaly indices and the 2- and 3-yr anomalies of Pacific herring abundance. Chi-square (χ^2) values are shown for each relationship. None of the values were significant ($P < 0.10$).

Fraser River discharge anomaly index	Strait of Georgia production	
	2-yr	3-yr
2-yr	3.0	
3-yr		3.21

presumably were common before discharge records were kept. If the interannual fluctuations have been common for centuries, it is possible that some species in the Strait of Georgia have adapted to this pattern of flow. Since 1976 there has been a declining trend in Fraser River discharge. If natural changes in discharge are occurring, it is important to recognize their impacts on marine survival and separate these effects from fishing and freshwater habitat effects when attempting to manage chinook and coho stocks.

The relationships between discharge and production anomalies may be useful in forecasting abundance changes. It is helpful to know if total coho catch in the Strait of Georgia could be higher or lower in the following year and chinook catch in 2 yr's time. However, the relationships apply only when extreme changes in discharge occur, and not when discharge is average or when consecutive years of above-average or below-average discharge occur. In 1990 and 1991, there were the first 2 consecutive yr of high discharge since 1922. In 1991, coho catches in the strait were extremely low (Fig. 8) and survival in general appears to have been low. The change to very low discharge in 1992 appears to be associated with very high catches of coho in the Strait of Georgia in 1993. However, 1993 was also a year of very low discharge, the lowest since 1945. The consecutive years of very low discharge in 1992 and 1993 were also the first since 1945 and it will be interesting to see how the catches of coho and chinook are in the Strait of Georgia in 1994 and 1995, respectively.

The value of the relationships in this report for fisheries management will improve as we understand more about the mechanisms involved. The pattern and possibly the amount of discharge are important but the physical and chemical composition of the bottom water that enters the Strait of Georgia as a consequence of the estuarine circulation probably is important also. We think that fisheries management will benefit from a better understanding of the relationships among Fraser River discharge and the marine environment.

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