Review of the Influence of Climate on Salmon

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Evidence suggests that the year-class strength of salmon populations is related to decadal scale climatic/ocean fluctuations. The interactions have complex latitudinal patterns and appear to involve the major food web and current structures of the North Pacific. To understand the effect of climate on Columbia River salmon the North Pacific system must be considered. A brief review of the patterns, the postulated mechanisms and indicators of the patterns follow. In general, two major climate regimes have been identified; one associated with cool and wet climate in the Pacific Northwest and another associated with warm and dry Pacific Northwest weather. The warm/dry regime favors stronger year class strengths of many Alaskan fish stocks while the cool/wet regime favors stocks on the West Coast of the lower United States. Within seasons climate factors related to the timing of the spring winds also have been shown to affect survival.

Fish and climate patterns

In general, multidecadal abundance fluctuations have been characteristic of fish stocks for centuries (Rothschild 1995) but an appreciation of the importance of climatic-fish fluctuations is relatively recent. The first significant and longest record of fish population fluctuations was obtained from a 2000 year sedimentary record off California and Baha, California. The abundance of Pacific Sardines and northern anchovy, inferred from scales in sediment cores, exhibited a fluctuating pattern over two millennia. A spectral analysis of the records had a peak at about 60 years (Smith 1978, Bumgartner et al. 1992, Sharp, 1992). The contribution of climate to these types of fluctuations was inferred from a nearly coherent pattern of catches of sardines (*Sardinops*) in fisheries around the Pacific basins (Kawasaki, 1984). One of the earliest papers documented the impact of the 1972-73 El Niño on the crash of the Peruvian anchovy fishery (Valdivia 1978). The significance of climate on fisheries variability has also been the focus of other treatises (Smith 1978, Gantz 1992, Beamish 1995 and others).

Studies defining the decadal scale ocean variability in the North Pacific have mostly emerged since 1990 and were often motivated by a striking shift in oceanic and biological conditions that occurred in the North Pacific between 1976 and 1977. The oceanographic literature reported the shift as a change in the intensity of the winter Aleutian Low pressure regime between 1976 and 1978 which caused a major and persistent change in oceanographic conditions and biological populations. The regime shift occurred as an abrupt change in the large-scale boreal winter patterns over the North Pacific. The change was marked by a southward shift and intensification of the Aleutian Low and prevailing westerlies over the mid-central and eastern Pacific (Graham 1994, Miller et al 1994). This produced a winter intensification of the Alaskan Gyre circulation and moved the east-west running subarctic boundary current further north, which in turn allowed warmer water from the south to move up along the west coast of North America (Emery and Hamilton 1985). This change in circulation produced a shift from a cooler to a warmer North Pacific sea surface temperature regime. The cool regime prior to 1976, produced by the weak Alaska Gyre circulation had enhanced upwelling along the west coast of North America. The warm regime, produced by the strong Aleutian Low after 1977, had a strong Alaska Gyre circulation and weak upwelling further south (Hollowed and Wooster 1992). Although two general regimes, which appear to have decadal scales, have been discussed in previous studies, Ware (1995) using a spectral analysis of twenty-one climate records identified four dominant time scales: a 2-3 year (quasi-biennial oscillation), 5-7 year (El Niño - Southern Oscillation, ENSO), 20-25 year bidecadal oscillation, (BDO), and a poorly resolved, very low frequency oscillation (VLF) with a 50-75 year period. Of his indicators, the bidecadal scale oscillation is most identified with the regime shift noted in 1977.

Accompanying the 1977 shift from a cool to a warm ocean temperature regime were significant changes in production throughout the marine food web. The intensification of the Aleutian Low (the warm regime) has been associated with increased phytoplankton (Venrick, McGowan, Cayan, and Hayward 1987) and zooplankton production (Beamish and Bouillon 1993, Brodeur and Ware 1992, McFarlane and Beamish 1992, Wickett 1967) in the subarctic domain, which includes the Alaskan current and Gyre. In contrast, the warming of surface waters correlated with decreased zooplankton abundance in the California coastal waters (Roemmich and McGowan 1995).

The oceanographic shift also affected fish stocks. Trends in total salmon catches in the warm regime, post 1977, increased primarily from increased production of pink, coho and chinook salmon from Alaska (Beamish 1993, Beamish and Bouillon 1993, Francis 1993, Francis and Hare 1994, Cooney et al. 1995). The pattern was particularly strong with Bristol Bay sockeye which jumped from catches on the order of one million fish in the early seventies to a record catch of 44 million sockeye in 1995 (van Amerongen 1995). The general trend was the same for pink, coho and chinook from Alaska with upward trends beginning in 1976-77 and continuing into the eighties (Beamish 1993). These Alaskan catches have also remained high in the 1990's. The pattern (comparing the 1950s to the 1980s) is also evident over a wide range of the Gulf of Alaska for sockeye, pink, chum, coho, chinook salmon and steelhead (Brodeur and Ware 1995).

A trend in chinook size also correlates with the regime shift with decreasing sizes from 1951 and 1975 and an abrupt shift with increasing average chinook weight starting in 1977-78. This pattern first appeared in the northern stocks, with some southern stocks showing the increasing trend beginning in 1983 while other southern chinook stocks did not exhibit the increase (Beamish 1993). In contrast, a declining size and increasing age at maturity were observed for chum salmon stocks from the western North America between 1972 and 1992 (Helle and Hoffman 1995) and in the North East Pacific, halibut have exhibited a decline in weight since 1976 (Parma 1995).

Other Alaskan coastal fisheries were also affected by the 1977 regime shift. In Pavlov Bay, Alaska, a 21-year trawl time series indicated that shrimp (*Pandalus borealis*) and capelin (*Mallotus villosus*) virtually disappeared between 1978 and 1979 while pollock (*Theragra chalcogramma*), cod (*Gadus macrocephalus*) and flat fish populations increased greatly and persisted throughout the 1980's (Anderson 1991). Pollock and cod stock fluctuations, as determined by commercial fishery statistics, showed the same trends (Alverson 1992). Warmer temperatures in the Bering Sea during walleye pollock early life history are conducive to strong recruitment (Quinn and Niebaure 1995). The same pattern of increase (comparing the 1950s to the 1980s in the Gulf of Alaska) is also reported for species of, shark, pomfrit, mackerel, albacore and squid (Brodeur and Ware 1995). The effect of the regime shift extended to other than fin fish as well. An index of oyster growth off Washington exhibited a decline after 1977 (Ebbesmeyer and Strickland,1995). Northern fur seal survival in the Pribilof Islands was positively correlated with air temperature (York 1995). Red king crab in the Gulf of Alaska and Bering Sea also exhibited increased catch with warm sea surface temperatures but on a decadal scale, the cycles of abundance and temperature had different periods (Muter, Norcross and Royer 1995).

Evidence indicates that regime shifts have opposite effects on high and mid latitude biological populations. A century long record of sardine catch exhibited a striking coherence over mid-latitudes of the Pacific Ocean. Isolated stocks of *Sardinopus* spps., from Chili the far east, and California had high catches about 1940 and 1990 with low catches in the 1970's. The catch statistics followed closely the sea surface temperature anomaly for the Pacific Basin (Kawasaki, 1984, Sharp 1992). In the higher latitudes of the North Pacific after 1977 salmon exhibited increasing catch trends from Alaska, Russia, Canada and Japan (Beamish and Bouillon 1993). On the other hand, West Coast salmon populations exhibited evidence of decline after the 1977 regime shift (Francis and Hare 1994, Richards and Olsen 1993). Furthermore, a 60-year data record between 1925 and 1985 showed that Gulf of Alaska pink and sockeye salmon catches were in phase, but they varied inversely with the catches of Washington / Oregon / California coho (Francis 1993). That is, the Alaskan catches were high when the West Coast catches were low and the pattern appeared to have a decadal scale variation. This inverse pattern with Alaska and West Coast stocks was also evident in survival of hatchery reared stocks. Coronado-Hernandez (1995) estimated survival of 8596 coho, 11051 chinook, and 1389 steelhead tag groups from Alaska to California. In general, stock survivals declined over most of the geographical range and were particularly notorious in the late 1970's and in the late 1980's. The Alaska coho exhibited the opposite trend with survival increasing in the late 70's and 80's.

The mechanism

Evidence indicates that North Pacific fisheries catches and survivals, marine biological production, the ocean currents, and the climate are linked. The linkages result in low frequency (with periods of decades) and often sudden shifts in production. The reason for these patterns is not well understood but a model has been proposed that is in agreement with patterns observed in plankton and fish stocks.

The model was proposed by Hollowed and Wooster (1992) and extended by Francis and Hare (1994) and is based on earlier oceanographic studies and theories of marine dynamics by Emery and Hamilton (1985), Ware and McFarlane (1989), Francis (1992), Francis and Sibely (1991), Wickett (1967) and others. In this hypothesis the strength of the winter atmospheric circulation in the North Pacific controls the intensity and location of the Aleutian low, which in turn affects the circulation of the Northeast Pacific currents including the eastward flowing Subarctic Current and its two coastal extensions, the Alaska current flowing north and the California current flowing south. Following the coast, the Alaska current returns to the west forming the Alaskan Gyre. The strength of the branches of this current system appear to have two general patterns or regimes. One regime is distinguished by a strong winter circulation in the Alaskan Gyre and is correlated with an intense Aleutian pressure low in the winter. The other regime is distinguished by a weaker Aleutian Low pressure and a weak Alaskan Gyre winter circulation. Intense Aleutian Lows strengthen the Alaskan Current at the expense of the California Current, while weaker Aleutian Lows have the opposite effect and strengthen the California Current and weaken the Alaskan Current.

These patterns affect upwelling and advection of surface currents into the coastal Upwelling Domain off the west coast of North America and the Coastal Downwelling Domain off Alaska and British Columbia (Fig. 1). An intense Aleutian Low allows warm sea surface water to move further northward and increases phytoplankton production in the Downwelling Domain. At the same time the Upwelling Domain intensity and its phytoplankton production both decrease (Ware and Thompson 1991). The current regimes may also affect the advection of Subarctic Current and Alaskan Gyre zooplankton into the domains. An intense Aleutian Low transports zooplankton into the Downwelling Domain and a less intense Low transports zooplankton into the Upwelling Domain off the west coast (Wickett 1967).

Two models have been proposed for the correlation between climate and phytoplankton, which in part drives the increased fish production. Venrick et al. (1987) postulated increased phytoplankton production is driven by increased vertical mixing during an intense Aleutian Low. Wong et al. (1995) suggest an alternative explanation. Recent work has indicated that iron is likely a limiting nutrient in the open ocean. Its source is atmospheric and so North Pacific phytoplankton production may be correlated with atmospheric transport of iron from Asia. In this scenario, larger iron transport during an intense Aleutian Low would increase phytoplanknton production in the Gyre.

The impact of the regime shifts on fish survival and production is complex and speculative. In general, it is thought that the Alaska fish stocks are favored by the warm regime because of increased phytoplankton production, which through the food web increases the forage base of fish in the Alaskan Gyre. The factors that increase the fish forage base in the northern Downwelling Domain in the warm regime decrease it for fish in the West Coast Upwelling Domain. In the cool regime the same factors appear to have the opposite effect. Predators also enter into the equation and here too the change between warm and cool water regimes may affect the distribution and abundance of predators. In particular, the movement of warm water mackerel northward during the warm regime may negatively impact survival of West Coast salmon smolts during their ocean entry. Finally, the climate regime shifts affect the freshwater habitat of salmon also. The interaction can be either positive or negative depending on the patterns of rainfall, snowpack, temperatures and runoff. For example, floods during the fall spawning period can severely degrade the redds and reduce egg survival while the same runoff in the spring may decrease smolt migration time and, along with increased turbidity, decrease exposure to predators.

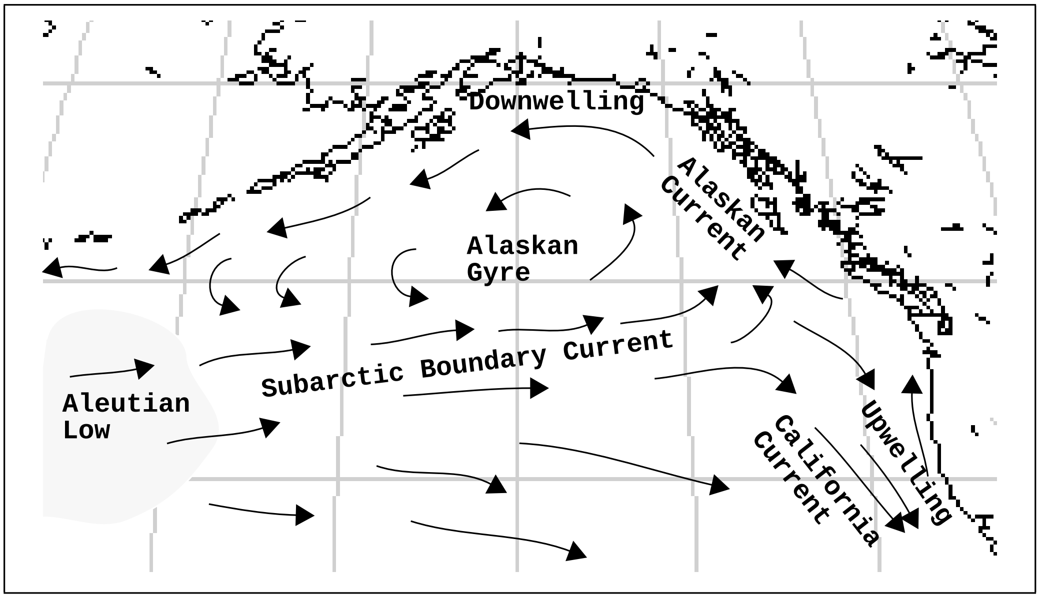

Fig. 1 Current structure and phytoplankton Upwelling and Downwelling Domains. A northward shift of the currents during years with an intense winter Aleutian Low favor higher productions of phytoplankton, zooplankton and fish in the Alaskan current system. Years with a less intense Aleutian Low favor greater food web production in the California Current. The shift between regimes appears to occur on a decadal scale.

Climate indicator

Relationships between weather and salmon are suggested in a variety of records. In these characterizations, a number of weather indicators have been identified including the Kodiak Winter Air Temperature (Francis and Hare 1994), the Central North Pacific winter atmospheric pressure index (Cayan and Peterson 1989), and the North Pacific Index (Trenberth and Hurrell 1994) to name a few. Many other environmental changes, both physical and biological, are also correlated with decadal scale climate changes. Ebbesmeyer et al. (1991) found changes in forty environmental indicators correlated with the 1976 regime shift.

For comparison with Columbia River salmon, the Pacific Northwest Index (PNI) developed by Ebbesmeyer and Strickland (1995) is potentially one of the most useful records. This is because it is a composite index that characterizes Pacific Northwest climate patterns in both coastal waters and freshwater habitats. In addition, it is a century-long record. The approach of using a composite climate index works because many environmental parameters in the Northwest are statistically related to one another, and thus they may be combined to furnish a broad scale understanding of the state of the Pacific Northwest environment. The PNI uses three parameters: air temperature at Olga in the San Juan Islands, averaged annually from daily data; precipitation at Cedar Lake in the Cascade Mountains, averaged annually from daily data; and snowpack depth at Paradise on Mount Rainier on March 15 of each year. For each parameter annual averages are normalized by subtracting the annual values from the average of all years divided by the standard deviation about the average. Finally, the three variables are averaged giving a relative indicator of the variations in climate. Positive values of the PNI indicate warmer and dryer years than the average and negative values indicate cooler and wetter years than the average (Fig. 2).

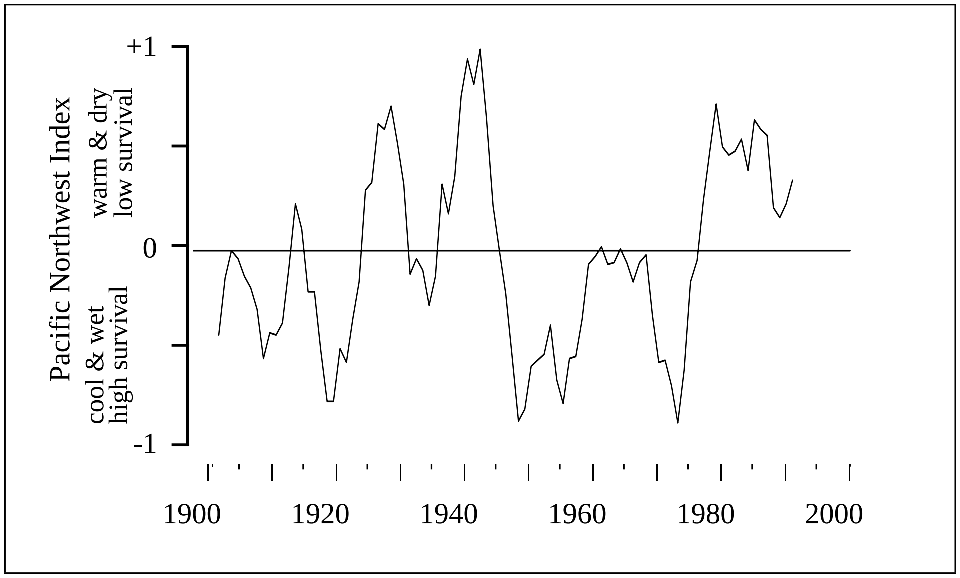

Fig. 2 Pacific Northwest Index characterizes cool / wet and warm / dry climate patterns in the Pacific Northwest.

As expressed by the PNI, the weather pattern switches between warm / dry and cool / wet regimes on about a 20 year period extending back to the 1900s. The cycle has had a distinctive double peak pattern with a strong regime shift followed by two weaker regime shifts and then another strong regime shift. The last strong regime shift occurred in 1977. If the pattern holds the recent cooler wetter Pacific Northwest weather may be a weak regime shift which would be followed by a more intense period of warm dry weather. The point is not that the PNI, or any other indicator, is a predictive tool (it is not) but that it illustrates that climate regimes shift quickly, have decadal duration, and have significant consequences.

The PNI shows a correlation with variations in the Columbia River spring chinook catch (Anderson in press). The cool wet climate pattern, which is characterized by negative PNI values, corresponds with above average Columbia River spring chinook catch and periods of warm dry weather correspond with lower than average catch (Fig. 3).

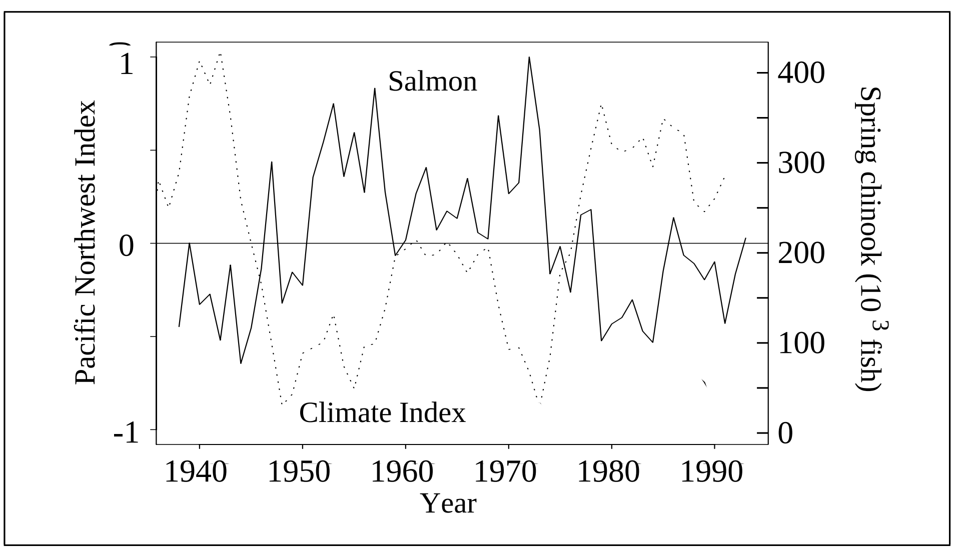

Fig. 3 Catch of Columbia River spring chinook is correlated with the PNI.

Year-class strength is affected by other factors besides decadal scale climate variations. Of particular importance is the short-term (weekly) variation in nearshore conditions when salmon smolts enter the estuary. An analysis of spring chinook transported from the Snake River (1983 through 1990) indicated that survival from the estuary to adult return was significantly correlated to the timing of ocean entry relative to the timing of the spring transition as represented by the latitudinal component of the coastal winds. Smolts entering the estuary early in the seasons (16-22 April) had an average adult recover of 0.11%; later migrants (19 April to 8 June) had an average adult recovery of 0.29% recovery (Hinrichsen, Anderson, Matthews, and Ebbesmeyer in press).

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