Effect of Climatic Variations on Salmon in Rivers of British Columbia

By Shruti Khanna

INTRODUCTION

Salmon comprise more than 50% of the total fisheries catch in British Columbia (BC) (FBC 2004). Five species of salmon are common in this region – chum, sockeye, chinook, pink and coho – along with the world's largest steelhead. The Skeena River watershed (figure 1), famous for its large runs of anadromous fishes, currently supports extensive commercial and sport fisheries and has been an intimate part of the livelihood of First Nation tribes living on the banks of Skeena and its tributaries (Marsden et al. 2002). The Upper Skeena watershed supports the bulk of the steelhead, chinook, coho and sockeye spawning runs. Although large tracts of the watershed are relatively unaffected by anthropogenic influences, logging, mining and farming activity are deemed to be a significant threat to steelhead and salmon productivity (FOC 2002). An additional threat that has been largely ignored by policy-makers and resource managers is associated with decadal scale climatic variability and global climate change.

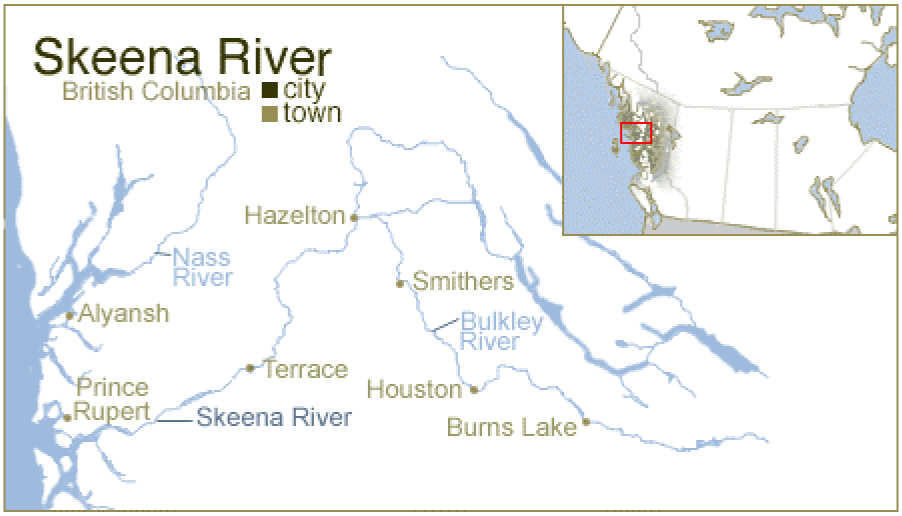


Figure 1: The Skeena River Watershed (TSR 2004)

Salmon spend part of their lifetime in the ocean and part in fresh water (rivers and lakes), so they are affected by conditions in both ecosystems. Environments in both these ecosystems are influenced by climate. Climatic changes in the Pacific Ocean have been studied extensively.

Three different scales of climatic variability have been identified. ENSO (El Niño Southern Oscillation) events cycle with a period of 2-7 years, PDO (Pacific Decadal Oscillation) events occur at decadal scales with a period of 50-70 years and long-term trends in climate due to global warming can be identified at the scale of millennia (Francis and Hare 1994, Hare and Francis 1995, Picaut et al. 2001, Mantua et al. 2002, Fiedler 2002, Mote et al. 2003). ENSO and PDO oscillations bring cycles of warm weather and cold weather conditions to the coast and inland in British Columbia. Long-term climate change is largely unidirectional with global temperatures showing a warming trend. In this paper, I explore the effects that warm and cold climate regimes have on salmon at different stages of their life cycle and how those effects are mediated through changes in habitat. I will also examine how the persistence of cold or warm weather at different time scales impacts salmon survival and reproduction.

LIFE HISTORY OF SALMON

Salmon (*Oncorhynchus spp.*) are anadromous fish, i.e. they swim up rivers and streams to spawn after spending most of their adult life in the ocean. After hatching, young salmon remain in the stream for a few weeks to several years depending on the stock, then swim downstream to the ocean. In the ocean, salmon grow to adulthood and live for several months to six years before returning to their spawning grounds. Among these species are a large number of genetically and behaviorally distinct populations, or stocks, which have evolved to take advantage of various niches by pursuing different migration strategies. The diverse behavior of different stocks makes them sensitive to environmental conditions in different ways, thereby buffering the genus as a whole against a catastrophic population crash (Mote et al. 2003). Table 1 shows the variation in life history characteristics of the five salmon species.

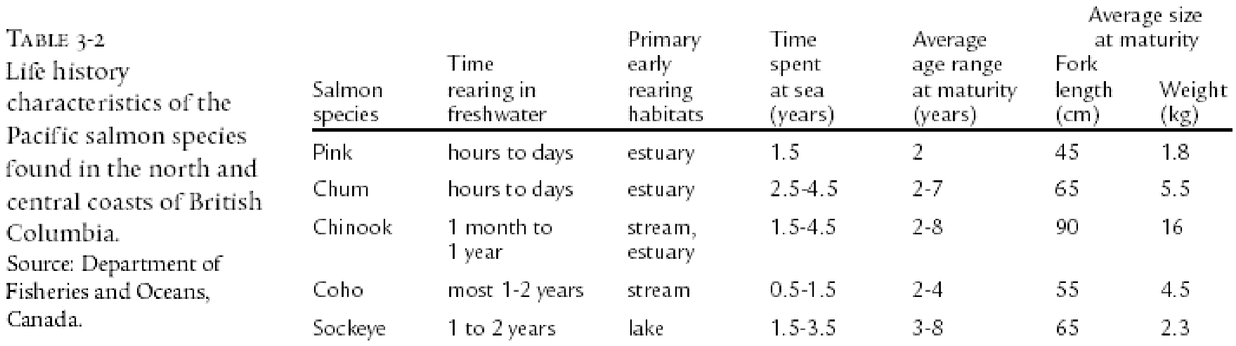


TABLE 3-2
Life history characteristics of the Pacific salmon species found in the north and central coasts of British Columbia.
Source: Department of Fisheries and Oceans, Canada.

Salmon species	Time rearing in freshwater	Primary early rearing habitats	Time spent at sea (years)	Average age range at maturity (years)	Average size at maturity Fork length (cm)	Weight (kg)
Pink	hours to days	estuary	1.5	2	45	1.8
Chum	hours to days	estuary	2.5-4.5	2-7	65	5.5
Chinook	1 month to 1 year	stream, estuary	1.5-4.5	2-8	90	16
Coho	most 1-2 years	stream	0.5-1.5	2-4	55	4.5
Sockeye	1 to 2 years	lake	1.5-3.5	3-8	65	2.3

Table 1: Life History Characteristics of Pacific salmon species. (Reimchen, 2002)

EFFECT OF CLIMATIC VARIABILITY ON SALMON

Ramifications of cold weather cycles

During cold climate cycles, more of the autumn/winter precipitation falls as snow, and the total winter precipitation is higher due to a wetter climate. The winter peak due to runoff is low, and the snowpack is large. Summer snowmelt peaks can be high causing high water levels and flooding in the rivers. High flow can lead to scouring of fish habitat, which exposes redds (pits in which the eggs are deposited) and leads to high mortality in eggs. However, less extreme wet and cold conditions favor cold-water fish like salmon. High flows facilitate migration of the salmon to and from the ocean and keep fresh water flowing through the redds. High flows also flush out fine sediments from the gravel and transport gravel downstream creating and enhancing salmon habitat for the coming year. Lower temperatures contribute to increased survival of adults and juveniles.

Ramifications of warm weather cycles

During warm climate cycles, more of the autumn/winter precipitation falls as rain resulting in a higher winter peak due to runoff. Less of the precipitation falls as snow leading to a smaller snow pack. Higher spring temperatures cause more of this snow pack to melt earlier and bring about an early spring freshet. The timing of the spring freshet plays an important role in the journey back to the ocean for juvenile salmon (Danard and Murty 1994, Mote et al. 2003). Salmon out-migration needs to be coordinated with the onset of upwelling and increased productivity in the ocean. This facilitates access to abundant food and protection from predators for the smolts (estuarine salmon) at the most vulnerable stage in their life cycle.

By the time the high temperatures of summer set in, there is not as much snow left to contribute to the river flow. This causes lower flows in summer that last for a longer period of time. Rivers are much more susceptible to atmospheric temperature changes due to their high surface to volume ratio. Low flows further increase this ratio during the summer, and when coupled with the higher atmospheric temperatures, lead to increased water temperatures in the river. Salmon can tolerate temperatures of up to about 24.5°C but prefer temperatures from 12 to

15°C. Warm water temperatures reduce salmon fitness, survival and reproductive success and promote potential long-term population declines (Tyedmers and Ward 2001). In a warmer environment, their metabolic rate increases, speeding up internal processes such as oxygen consumption, digestion and mobility. For example, sockeye salmon prefer the coldest temperatures of all five salmon species (Tyedmers and Ward 2001). Temperatures above 15°C can cause stress in sockeye, depleting their energy reserves, making them more susceptible to disease and reducing their capacity to produce viable eggs and sperm. Temperatures above 18°C can impair their swimming ability, and exposure to temperatures in the 20's for several days can result in death. Fish may die while in transit up the river (en route mortality), or they may not spawn when they arrive at their spawning grounds (pre spawning mortality). In the Fraser River in recent decades, en route mortality has been more than 50% and pre-spawning mortality has ranged between 0 to 80% for sockeye salmon (Tyedmers and Ward 2001). En route mortality has been shown to be much higher in years with warm river temperatures and particularly strong during the summer run when temperatures are at their highest (Tyedmers and Ward 2001). Figure 2 graphically illustrates the effect that the various changes due to climate warming have on sockeye production at different stages in their life cycle.

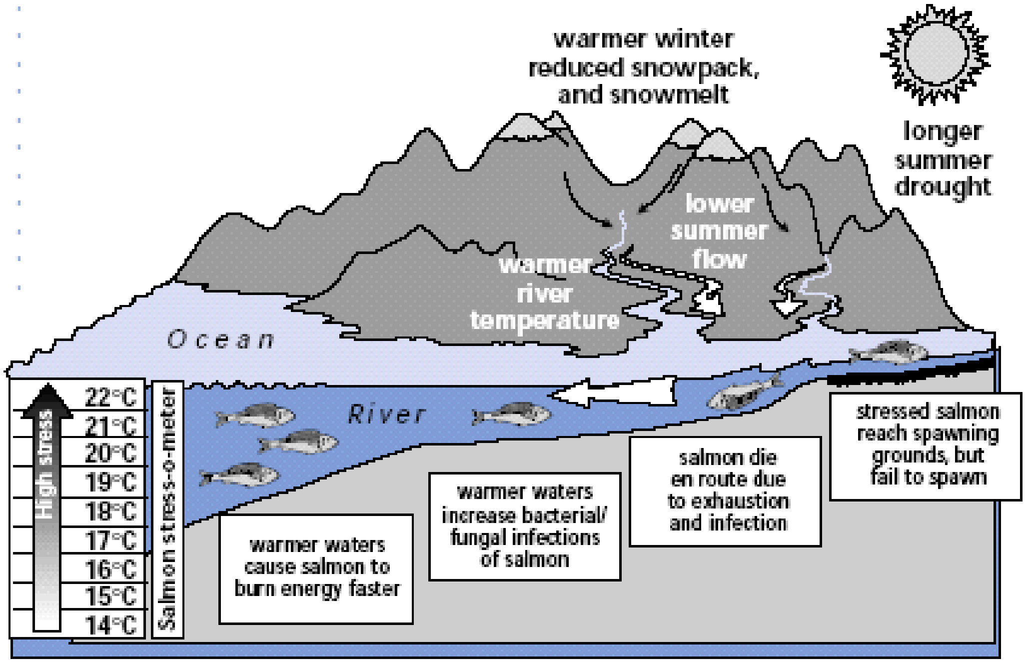


Figure 2: Life history of sockeye salmon as affected by climate change (Tyedmers and Ward 2001).

Effect of PDO and ENSO cycles on salmon

Extensive research in factors affecting abundance of fish has previously highlighted the importance of El Niño weather patterns on fish recruitment and survival in the tropics and subtropics (Picaut et al. 2001, Fiedler 2002). The fisheries in the eastern and western North Pacific regions, however, seem to respond to decadal scale changes rather than ENSO events that persist only for a period of to 6 to 18 months occurring with a periodicity of 2-7 years. In the early 1900s, researchers noticed a large-scale climate pattern that seemed to dominate the Northern Pacific waters (Nitta and Yamada, 1989, Trenberth, 1990, Wallace et al, 1993), later to be termed the "Pacific Decadal Oscillation" or PDO (Mantua et al. 1997).

The extreme phases of the PDO have been classified as being *warm* or *cool*, as defined by ocean temperature anomalies in North Pacific Ocean. Though the causes behind the PDO are still under investigation, the characteristic pressure, wind, temperature and precipitation patterns correlated with the phases of the PDO are well known. Sea surface temperatures (SST) in the central North Pacific are anomalously cool while SSTs along the coast of North America are unusually warm during the positive phase of the PDO. The sea level pressures (SLP) show an intensified low pressure cell centered on the Aleutian Islands during the positive PDO phase coinciding with anomalously high SLPs over western North America and subtropical Pacific. During the negative phase of the PDO, the observed SST and SLP anomalies are reversed. This step-like shift in the mean state of SLPs and SSTs in the North Pacific was first reported by Nitta and Yamada (1989) and has since been analyzed in great detail (Trenberth 1990, Wallace et al., 1993, Nakamura et al. 1997, Dettinger and Cayan 2000). Mantua et al. (1997) termed the phenomenon, the "Pacific Decadal Oscillation" and identified it as an oscillation between two alternative states as described above. They also developed a PDO index to track this oscillation. The PDO Index is calculated by spatially averaging the monthly sea surface temperature (SST) of the Pacific Ocean north of 20°N during the cooler winter months because year-to-year fluctuations are most apparent in those months. Other indices based on SLPs and the intensity of the "Aleutian low", have also been developed.

Figure 3 shows the SST, SLP and wind stress distributions during warm and cold phases of the PDO and depicts a comparison with behavior of ENSO. During positive PDO, due to increased temperatures on the sea and land, more of the winter precipitation falls as rain resulting in reduced snowpack. During negative PDO, cooler temperatures result in heavier winter snowfall, increased snowpack and lower snow elevations. ENSO warm and cold phases have the same effect on climate but with much lower intensity in the north pacific coast of North America. From figure 3 it can be seen that the effect of the PDO is prominently in the northern Pacific region while ENSO impact is concentrated in the tropics. The PDO appears to oscillate between warm and cool phases every twenty to thirty years and has a tendency for multiyear and multidecadal persistence with a few instances of abrupt sign changes, while ENSO events seem to occur for a period of 6 to 18 months. The time periods of 1900 to 1924, 1947 to 1976, and 1998 to present correspond to the negative, cool phase of the PDO. The rest of the time period in the 20th century corresponds to the positive, warm phase.

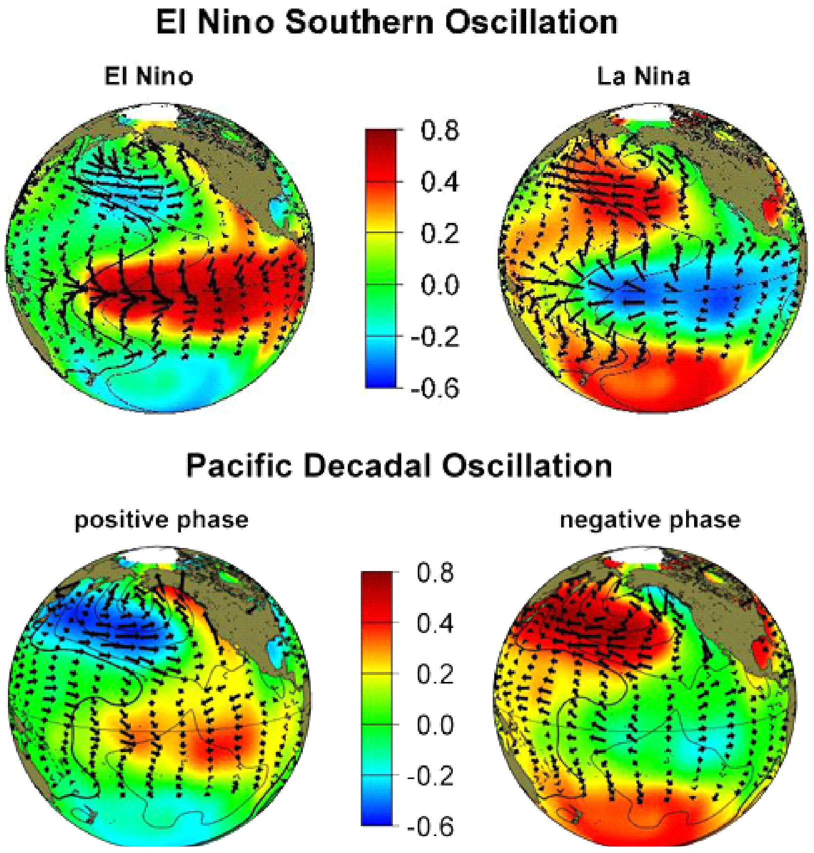


Figure 3: Comparison of the ENSO and PDO effects on sea surface temperature in the Pacific Ocean (Mantua and Hare, 2004)

The period of ENSO being much smaller than that of PDO, there are typically several ENSO cycles embedded in one PDO oscillation. This results in various combinations of temperature and precipitation. Combinations that augment each other (warm and dry, cool and wet) produce large anomalies in climate, snowpack and streamflow. When the ENSO and PDO are out of phase, the effect on climate is muted and closer to the mean as shown in figure 4.

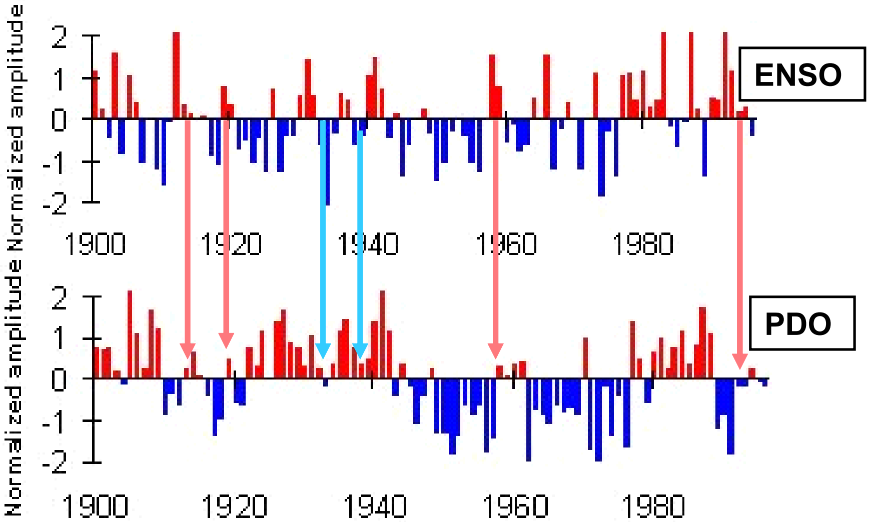


Figure 4: Blue arrows show depressed PDO values during positive PDO regimes due to cold ENSO periods and red arrows show depressed PDO values during negative PDO regimes due to warm ENSO periods. The peaks in the PDO also coincide with periods when both PDO and ENSO are in the same phase (Adapted from Mantua and Hare, 2004)

PDO and ENSO effects on streamflow

PDO and ENSO events affect the annual streamflow of BC Rivers, particularly the magnitude and timing of their seasonal streamflow. Streamflow in the Columbia River in BC shows a strong correlation with both ENSO and PDO. Warm-phase years see lower accumulation of snowpack and an earlier shift from snow accumulation to melting. Average annual flow in the Columbia is 10% below average with a larger reduction of peak flow in June (Neal et al. 2002). The effects of ENSO and PDO are additive, so years where both are in their warm phase produce low snowpack and streamflow, and the highest incidence of droughts (Mote et al. 2003). Similarly, the combination of cold phases of ENSO and PDO bring about the highest flows and greatest risk of flooding. Figure 5 (a and b) shows the correlation between Columbia flow and the PDO index.

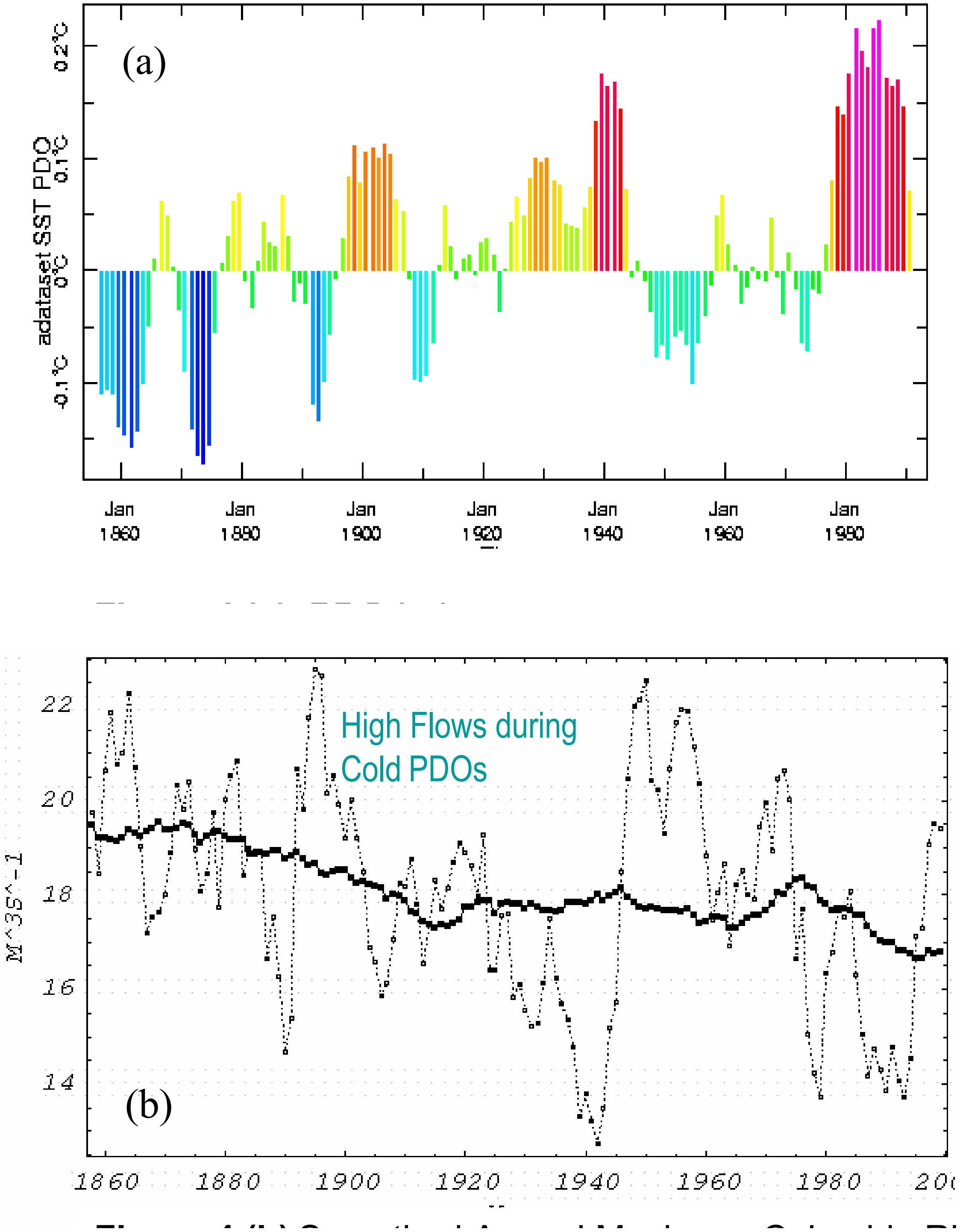
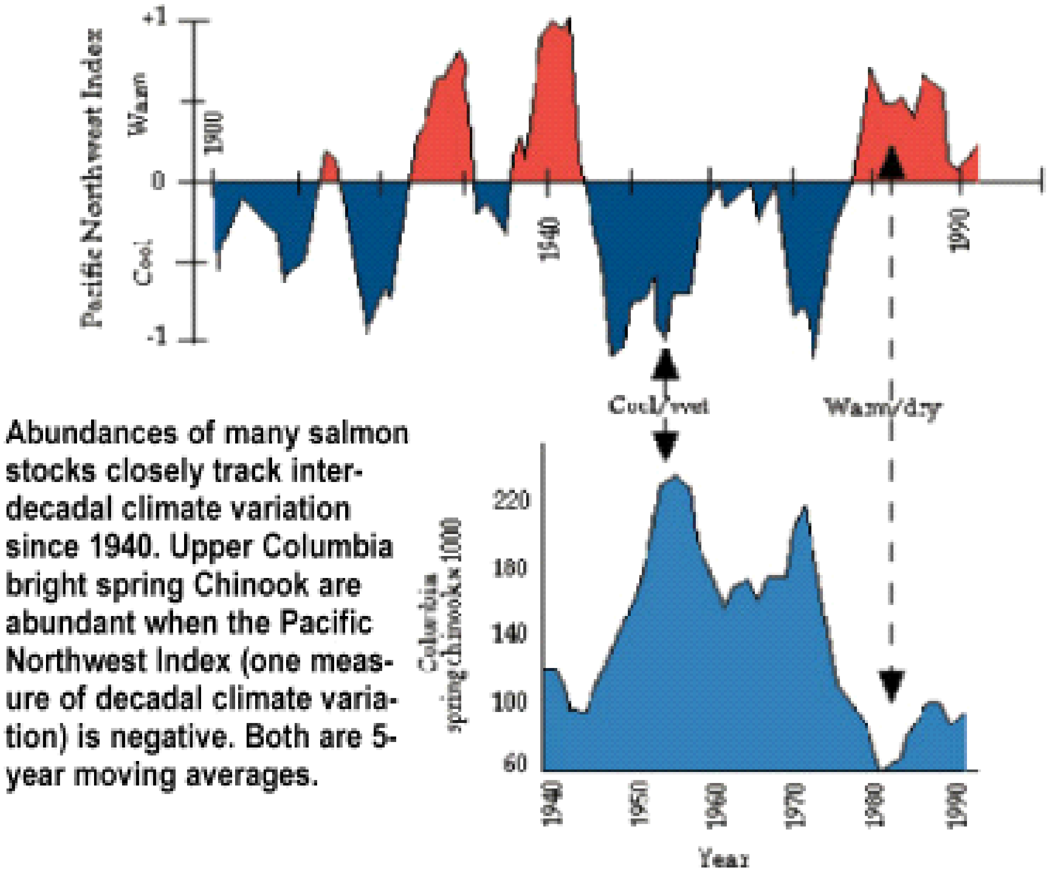


Figure 5: (a) The PDO Index. **(b)** Smoothed annual maximum Columbia River flow and trend.

Effect of changes in streamflow on salmon

Catch history of 70 years for Pacific salmon provides the first definitive link between the PDO and North Pacific fisheries (Mantua et al. 2002). There is a strong association between PDO variability and Pacific salmon production (Francis and Hare, 1994, Hare and Francis, 1995, Hollowed et al. 2001). During positive PDOs, winter flooding, lower summer flows and higher temperature in the river causes high salmon mortality and salmon stocks decrease. During negative PDOs, higher summer flows and colder temperatures favor salmon survivability and salmon stocks rise. ENSO events also impact salmon production through amplification or dampening of the PDO climatic regime. Figure 6 shows the relationship between salmon stocks in the Columbia River in BC and the Pacific Northwest Index, which is another index used to track PDO-like conditions.



Abundances of many salmon stocks closely track inter-decadal climate variation since 1940. Upper Columbia bright spring Chinook are abundant when the Pacific Northwest Index (one measure of decadal climate variation) is negative. Both are 5-year moving averages.

Figure 6: Columbia River salmon stock variability with climate (Mantua et al. 2002).

The limitations of scale

To identify cause and effect between two variables, it is necessary to look at the appropriate scale. The PDO has a period of 50-70 years with a phase change every 20-30 years. To detect a correlation between PDO and salmon catches, the time series should ideally include at least a few periods. At present we have a PDO index that goes back to 1900 and a salmon catch data going back to 1924. However, researchers have tried to reconstruct both of these time series using other creative approaches. Minobe (1997) reconstructed continental surface temperatures that suggest PDO-like climate variability with a recurrence interval of 50-70 years. These fluctuations can be traced back to three centuries. In a similar study using tree ring width chronologies, Gedalof and Smith (2001) determined that regime shifts had occurred 11 times since 1650 but did not appear strongly in the interval from 1840 to 1930. These studies give credence to the fact that the PDO may not be a transitory phenomenon but may actually be a centuries' old pattern in climate.

Drake et al. (2002) reconstructed salmon abundance back to 1820 A.D. using Sitka spruce and white spruce growth rates in Alaskan Pacific coastal rainforests. These riparian tree species grow 1.5 to 3 times faster in streams where fish come to spawn. They found that the PDO was correlated with the salmon catch patterns over the last 75 years. Before 1900, salmon abundance cycled with 20-35 year periodicity. Finney et al. 2000 reconstructed sockeye salmon abundance for last 300 years in Bristol Bay and Kodiak Island regions in Alaska using high resolution lake sediment records of ^{15}N, diatoms and cladocerans. They found a consistent relationship between salmon production and sea surface temperature (SST), though other factors also played a role. SST is highly correlated with the PDO as discussed earlier, so it may be inferred from the above that salmon production is also correlated to PDO. No study has yet attempted to verify a reconstructed salmon production record with a reconstructed PDO record, which has the potential to yield interesting results. In examining longer time series, it becomes easier to delineate natural influences from anthropogenic factors and observe the correlation between climatic regimes and salmon production free from human impact.

Effect of long-term climate change on salmon

Average annual temperature in BC has warmed by 0.6°C on the coast, 1.1°C in the interior, and 1.7°C in northern BC in the 20th century (Tyedmers and Ward 2001). Precipitation has increased 2-4% per decade in southern BC. Sea surface temperatures (SST) have increased 0.9 to 1.8°C along the BC coast, and sea levels have risen 4 to 12 cm. As a result, lakes and rivers are becoming free of ice earlier in the season, river flows in spring are larger in volume and peak magnitude, and summer water temperatures are warmer (Tyedmers and Ward 2001). The Skeena River is snowmelt-dominated and has a characteristic annual flow pattern with two asymmetric peaks, a major one associated with summer snowmelt and a minor one due to autumn/winter rains (figure 7(b)). Data from a river with a similar hydrograph are shown in figure 7(a). As discussed above, warmer climate leads to an earlier spring snowmelt, longer periods of low flow and higher winter runoff peaks (figure 7(a)). But the continuing trend of long-term climate change has the potential to permanently pull back the date of the spring freshet to earlier in the season. Outward migration patterns of wild juveniles may change due to this early freshet or due to warmer streams that force them to mature sooner. When they arrive at the river mouth, estuarine and ocean conditions may not match those that they have evolved with since the strength and seasonality of upwelling in the ocean appears unlikely to change in a warming climate (Mote et al. 2003).

Over the long term, higher temperatures are expected to result in a shift in the distribution of salmon to higher latitudes and elevations, and an increase in population fragmentation in more southerly parts of their ranges (Tyedmers and Ward 2001). This is particularly threatening to the survival of exceptionally cold-water adapted species like sockeye salmon and may result in a contraction of their range as well as a shift to higher latitudes and altitudes. There is also an increased likelihood of successful invasion by non-native species that require warmer water temperatures. Non-natives further threaten the survival of native species as they often compete with salmon for food and even feed on juvenile salmonids.

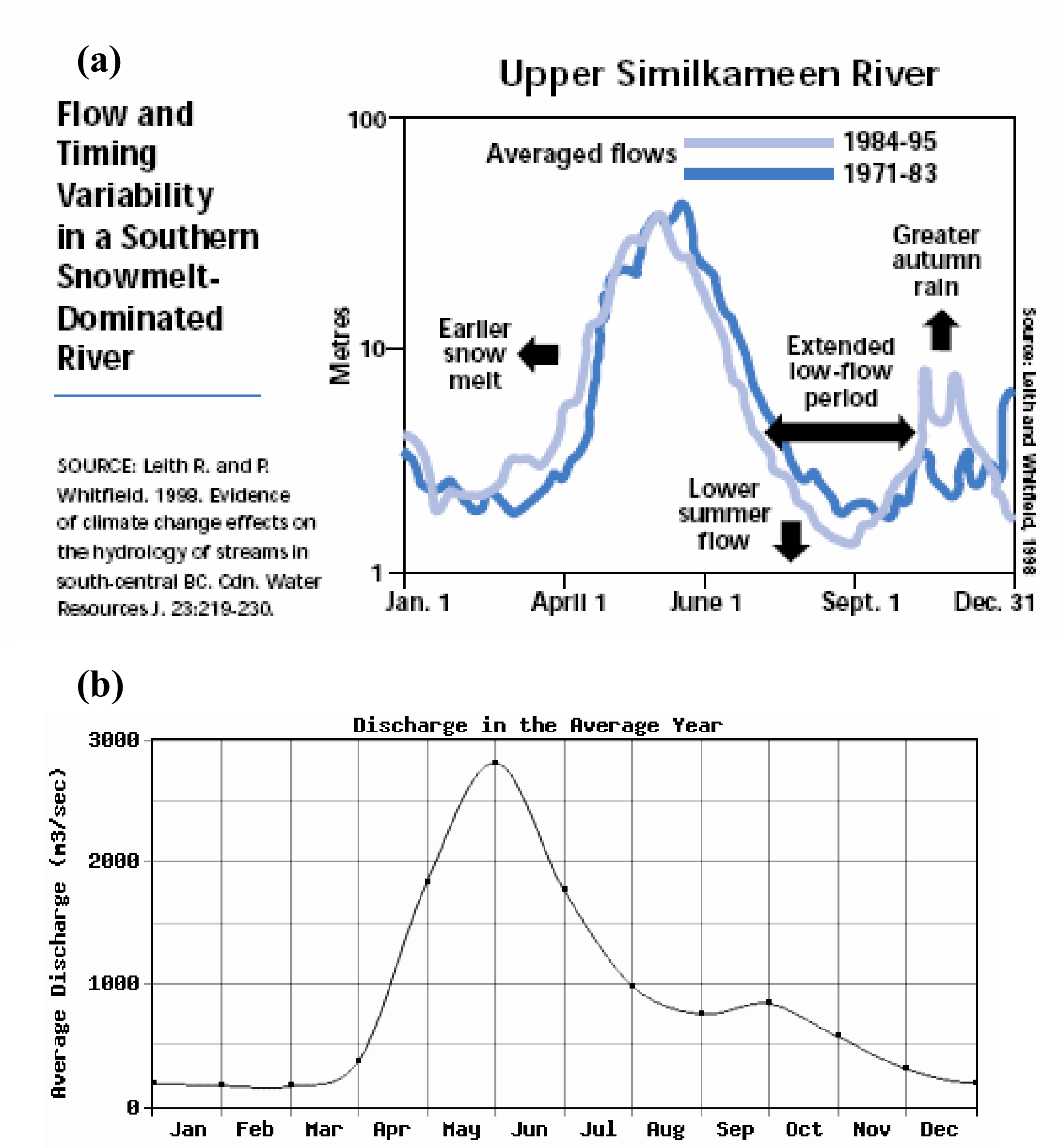


Figure 7: (a) Long-term change in the flow and timing of a southern snowmelt-dominated river. (Tyedmers and Ward 2001) **(b)** Discharge in the Skeena River in an average year (GRDD 2003)

Effect of climatic variability in the sea on salmon

Warmer sea surface temperatures cause increased mortality in juvenile salmon, changes in ocean distribution, changes in timing of migrations and decreased size of returning fish. During warm years, ocean productivity is relatively low, resulting in slower growth in juvenile salmon and higher competition for food, both of which increase vulnerability to predation (Tyedmers and Ward 2001). Subtropical fish (e.g. mackerel), migrating northwards during warm years may compete for food or prey on young salmon, further depressing the stock. In warmer years, evidence suggests that sockeye arrive later at the mouth of the Fraser River and may reach their spawning ground late. Late spawning can have a negative effect on the time when young salmon emerge the following spring and their subsequent survival (Tyedmers and Ward 2001). Fish may also congregate within a smaller habitat (due to decrease in habitable area) and compete for limited food supplies. This may cause slower growth, and returning fish may be smaller than normal. Combination of all the above factors in warmer years raises the expectation that warming of the climate will negatively impact fish stocks both in the river and the ocean, further compounding the total effects.

Conclusion

Salmon are anadromous, spending part of their life cycle in freshwater and part in the ocean. Consequently they are sensitive to changes in both the marine and freshwater ecosystems. Human encroachment into riverine landscapes and coastal waters, heavy commercial fishing and the impending danger of climate change has increased the extinction risk of declining salmon stocks. Salmon are an ecologically important species supporting vast food webs in oceanic, estuarine and freshwater ecosystems by providing nutrients every year during their migration to the rivers and lakes to spawn (figure 8). They are also a major part of commercial, native and sports fishing in British Columbia.

Climate in the North Pacific goes through warm and cold cycles at various scales that affect the British Columbia (BC) coastline and the inland climatic and environmental conditions. Cold climatic cycles are generally beneficial, while warm cycles reduce reproductive output and fitness of salmon. Pacific salmon catches are highly correlated with the pacific decadal oscillation (PDO), which has warm and cold phases that persist for decades. BC salmon production is generally increased during cold PDOs and decreased during warm PDOs. This effect is magnified when ENSO and PDO are in phase and dampened when they are out of phase.

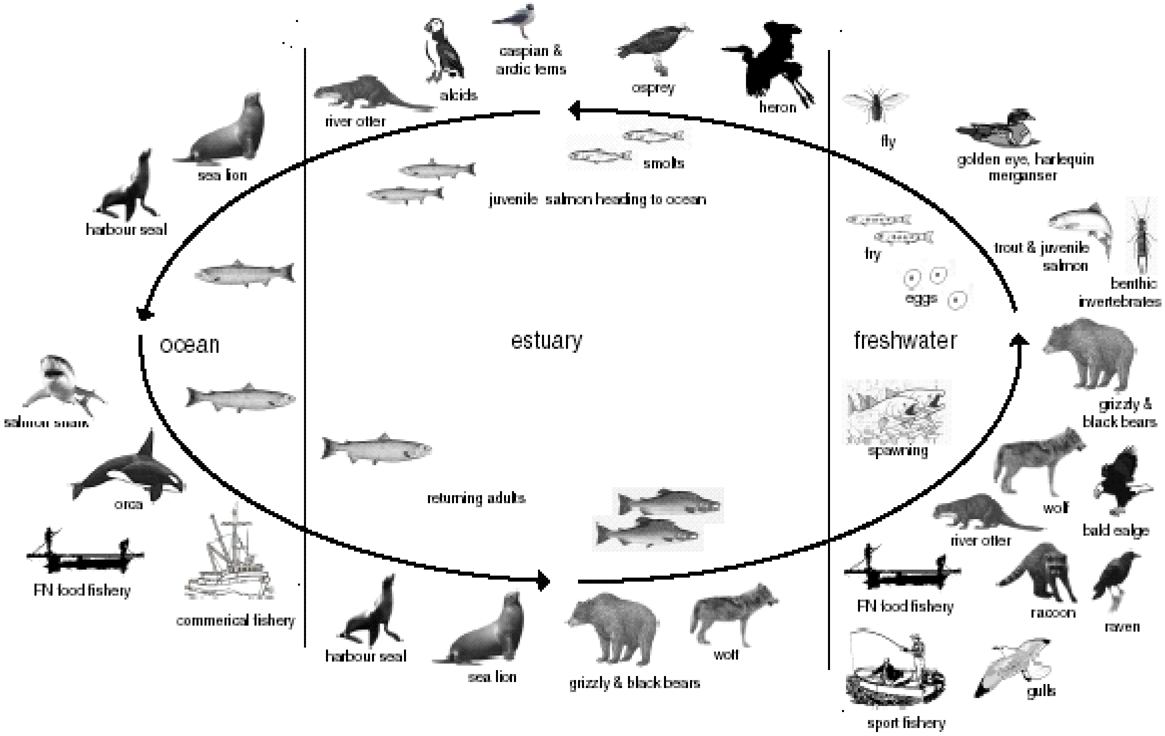


Figure 8: Food web beneficiaries of Pacific salmon in freshwater, estuary and ocean environments (Cederholm et al. 2000).

Global warming has led to an overall increase in the mean seasonal temperatures in BC. The Canadian model CGCM1 suggests that by 2030 British Columbia will experience an increase in mean annual temperature of 2°C and increased precipitation in winter (Tyedmers and Ward 2001). Evolution is a much slower process than climate change and cannot hope to keep up with pace of changing climatic conditions. Increasing temperatures have led to a change in timing of the spring freshet (first snowmelt in spring) of BC's snowmelt dominated rivers. The freshet now occurs earlier in the year, summer flows are lower and river water temperatures in the summer are higher than before. This results in higher mortality rates, especially among the salmon that come to spawn in summer. Higher mean temperatures are also affecting the range of the salmon, especially sockeye whose optimum temperature range is colder than other salmon species. The range of these species is expected to contract resulting in reduced distributions and increased potential of endangered status or extinction.

Coinciding warm phases of the PDO and ENSO should be closely watched since they give rise to extreme warm conditions in the oceans and rivers. Should warming trends continue, these overlapping cycles have the potential to shift ecosystems to alternative states that may be detrimental to salmon survival and result in local extinctions. The ability of PDO phases to persist for decades raises the possibility that during the next positive phase, if average global temperatures were higher, BC might experience 2 to 3 decades of record high water temperatures. This could be disastrous for wild salmon stocks, especially in the southern limits of their range. There is critical need for further research on the impacts of climatic regimes on water temperatures at smaller time scales. It is unclear if we can reverse or contain the effects of climate on salmon production, but sound scientific knowledge is a powerful tool to advance us in that direction.

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