The effects of climate on Pacific salmon
- A Summary of published literature

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Background

This is a summary of the published studies of the effects of climate and climate change on Pacific salmon. The summary reports the results of the research in a way that is readable for the general public. Consequently, the standard approach of referencing the various statements to appropriate papers is omitted. Instead, we produced an annotated bibliography of approximately 350 papers that is available from the North Pacific Anadromous Fish Commission (www.npafc.org).

This summary has been reviewed by a number of scientists, but it also reflects the interpretation of the authors. Thus, readers are encouraged to look through the bibliography and read the original papers on topics of particular interest. Readers will notice that there are different interpretations of the impacts of climate on Pacific salmon, but there is also agreement on many issues. One important agreement is that the current abundances of Pacific salmon are at historic high levels of abundance. This indicates that, in general, the recent climate is favourable for Pacific salmon production. However, not all species and not all stocks are prospering. The reasons for the high abundance of Pacific salmon and the low abundance of some species and stocks are not well understood. Improvements in understanding can be made most effectively through a cooperative approach among all researchers. The North Pacific Anadromous Fish Commission provides the organization that facilitates the international cooperation on the planning and research and monitoring of biological and physical factors that affect the production of Pacific salmon. A Long-term Research and Monitoring Plan (LRMP) has been produced and is available from the North Pacific Anadromous Fish Commission at www.npafc.org. Readers of this summary will find additional detail about the science that is needed to improve the forecasts of how Pacific salmon will respond to future changes in climate in the LRMP.

R.J. Beamish, June 2009

Canada

Pacific salmon continue to be the species that are of principal interest to British Columbians even though their commercial value has declined substantially. The specific factors that regulate Pacific salmon abundance and are responsible for the recent declines are not well understood, making it difficult to predict the impacts of climate altered ecosystems. However, it is generally accepted that climate related changes that could occur in fresh water and the ocean will have a major impact on the population ecology of Pacific salmon. Physical changes in winds, currents, temperature, precipitation, groundwater discharge and increased ice-free periods for lakes would affect the spawning, hatching, early rearing phases, survival, growth and distribution of salmon species. Even the timing of migrations of Pacific salmon back to their natal rivers may be affected.

The Fraser River drainage in British Columbia is a major producer of Pacific salmon, accounting for 30 to 40% of all Pacific salmon produced in Canada. Because numerous stocks of sockeye, pink and chum salmon are at or near the southern limit of their range, the early impacts of climate change should be detectable in these stocks first. In one study, potential impacts during their freshwater life were identified as a series of hypotheses:

- Warmer climate will increase water temperatures and decrease flows during spawning migrations, increasing pre-spawning mortality and reducing egg deposition;
- Warmer climate will increase water temperatures during egg incubation stages, causing premature fry emergence and increased fry-to-smolt mortality;
- Warmer climate will increase the severity and frequency of winter floods, thereby reducing egg-to-fry survival rates.

Almost all sockeye salmon spawn in rivers that flow into or out of lakes. After hatching, fry move into the lake where they usually remain for a minimum of one year. Although there is uncertainty about how lakes will respond to a warmer climate, excessive warming may impede the ability of young sockeye salmon to grow to sizes necessary for survival in the ocean. Furthermore, a decrease in size at maturity has been shown for Fraser River sockeye stocks over the past 42 years, coinciding with an increase in sea surface temperature in the ocean. The mechanism for this decrease in growth is unknown but could result from increased metabolic demand, oceanic changes that affect food availability, or both. A decrease in size and energetic reserves may exacerbate the impacts of warmer rivers during spawning migration. In the late 1990s, abnormally high pre-spawning mortality occurred and one of the explanations related the mortality to changes in climate. Variation in body energy stores of Fraser River sockeye salmon occur between years of low (1999, 2000) and high (1956, 1957, 2001, 2002) oceanic productivity. The importance of these energy stores is observed in years when upstream migration is most arduous, often resulting in increased pre-spawning mortality. These reserves are believed to be necessary for successful migrations and somatic growth. For example, energy stores for Stuart River sockeye salmon stocks are critical to their successful spawning after such a long river migration. Therefore, it is highly probable that there will be a direct relationship between increased river temperatures and pre-spawning mortalities for sockeye salmon and for all Pacific salmon species. Depending on the stock or spawning conditions, energy requirements may be different. Bioenergetics models can successfully backcast the effects of sea surface temperatures on Fraser River sockeye salmon growth. For example, a 3.5°C increase in sea surface temperature can cause a 14% reduction in average size at maturity.

Winter water temperatures in fresh water are related to groundwater base flows, lake water runoff, precipitation levels and perhaps changes in snowmelt patterns. It is probable that both summer and winter temperatures will be higher. These changes are particularly relevant for coho, sockeye and some Chinook salmon that remain in fresh water during their first year. Warm summer water temperatures may be too high for optimal growth and may force young salmon into suboptimal habitats. Poor growth in fresh water may contribute to increased mortality in the ocean. Recommended freshwater temperatures for most Pacific salmon range from about 7-16°C, with extremes from 3-20°C. Upper lethal temperatures are 25-26°C. Southern rivers could approach these higher limits under projected climatic scenarios. In the ocean, low temperatures can restrict feeding areas. Consequently, ocean warming, particularly in the winter, could favour the production of Pacific salmon in northern areas. However, the impact of climatic warming on winter water temperatures in the ocean is uncertain.

Decadal-scale regime shifts cause climate and oceanic changes that can abruptly reorganize ecosystems over large regions. Climate and ocean conditions changed in 1925, 1947, 1977, 1989 and 1998. The 1998 and 1989 regime shifts, however, were observed over smaller area scales and were not necessarily reversals or variations of previous regimes. Because natural fluctuations or changes in abundance can be dramatic and sudden, natural trends as well as the biological and physical mechanisms within the regimes need to be better understood. Thus, it is necessary to separate natural impacts from fishing effects and understand how greenhouse gas associated warming will interact with natural climate changes. For example, will the mechanism that causes regimes to shift be exacerbated or muted by the increasing levels of greenhouse gasses?

Not all species of Pacific salmon and not all regions are affected equally after regime shifts. Regimes may force opposite effects on the same salmon species in different sub-regions or opposite effects on different salmon species in the same region. In a given marine ecosystem, the effects of regime shifts are evident in lower trophic levels first but it is the response of fish that may provide the first convincing evidence of a change.

The short life cycle of pink salmon, as well as their abundance and extensive distribution, makes them a useful model species for studies of environmental impacts such as greenhouse gas-induced climate change on the long-term population dynamics of all Pacific salmon. The single year class and the short life span facilitate the understanding of associations between climate change and production estimates. Pink salmon also are associated with a long history of careful management and extensive scientific studies in British Columbia. An increase in marine survival in 2000 coincided with a major shift in the trend of climate indicators in 1999. Thus, there is solid evidence that pink salmon respond to climate changes in a time frame that could be used to detect the impacts of greenhouse gas-induced climate change.

It is probable that future responses by British Columbia stocks north of 50-55°N will be different than by southern stocks, based on persistently observed historical oscillations in productivity between northern and southern stocks. In the ocean, the major sources of early marine mortality may become more variable and more extreme. Predation may increase as more pelagic predators such as Pacific hake and mackerel move north. This predation mortality is related to growth and may become more important and more variable. Although it may be possible to mitigate climate related changes in fresh water, adjusting management at a stock level to adapt to climate related changes in the ocean would range between challenging and impossible. However, if climate impacts could be identified, it may be possible to use this information to convince Canadians and others that reductions in greenhouse gases are essential for the protection of Pacific salmon at their southern range.

The eastern North Pacific Ocean is dominated by north-south currents which maintain an offshore and coastal boundary. In this region, sockeye, pink and chum salmon migrate along the coast for their first marine summer and spend their first winter offshore. Chinook salmon, coho salmon and steelhead trout can also migrate offshore but tend to remain in coastal and shelf habitats. The extent and duration of global warming related climate changes in these areas is unknown. There are differences in thermal limits between chum, pink, coho and sockeye salmon north of the southern boundary of the transition zone. These thermal limits play a role in containing the offshore distribution of a species. It is not known how these temperature boundaries will change and if they change, how the various species and stocks will respond.

Pacific salmon are well known for their homing ability from feeding areas in the open ocean to the exact areas of their origin in coastal rivers. Less well known is their ability to stray. This straying rate is estimated to reach up to 10% and provides Pacific salmon with an ability to adapt to large-scale climate change such as past periods of glaciation. Pacific salmon tend to stray more than other species and thus are a good indicator of climate related changes that affect the return of salmon to their spawning rivers. Five species of Pacific salmon have been reported in Canadian Arctic waters, with pink salmon being the most frequently and Chinook salmon the least frequently observed. Recently, the first records of sockeye and pink salmon from Sachs Harbor on Banks Island were reported in the Beaufort Sea.

Hatchery fish contribute significantly to catches in Canada, as in other countries, but the impact of hatchery fish on wild fish is not understood. There has been a recent decline in the proportion of hatchery coho salmon in the Strait of Georgia which is a direct result of declines in the abundance and marine survival of hatchery coho salmon, as wild coho salmon abundances have remained relatively stable but at low levels. Wild and hatchery coho salmon respond differently to environmental changes and should be examined differently in a changing climate. Growth, survival and abundance relationships are exhibited earlier in the year for wild coho than hatchery coho salmon. Growth between July and September is inversely related to marine survival indicating that faster and earlier growth may improve lipid storage, increasing the chances of survival over the winter. Thus, when interpreting the impacts of climate, wild salmon must be studied separately.

Japan

Chum salmon are the major Pacific salmon produced in Japan and virtually all are produced in hatcheries. Chum salmon spend their early marine life in the coastal waters of northern Japan, their first summer in the Sea of Okhotsk and move into the Western Subarctic Gyre during their first winter at sea. Migrations then occur between summer feeding grounds in the Bering Sea and winter grounds in the Gulf of Alaska before returning to their natal streams and rivers to spawn.

In the late spring juvenile salmon begin to migrate into the Sea of Okhotsk from Hokkaido and East Sakhalin. The winter weather system which is called the Aleutian Low, strengthened between 1977 and 1988, resulting in decreased sea surface temperatures and the expansion of sea ice in the Sea of Okhotsk. This resulted in decreased zooplankton biomass in the western North Pacific. Immature Pacific salmon overwintering in the western North Pacific experienced high mortality due to decreased sea surface temperature and zooplankton biomass. Ocean growth and size at maturity decreased but have recovered and increased since the mid-1990s. After 1989, the Aleutian Low weakened causing sea ice to decrease and juvenile Pacific salmon survival to increase.

Studies from 1991 to 1998 suggest that both intra- and inter-specific density dependant effects regulate growth variation in Pacific salmon species. At higher abundances the average size of individual salmon may be smaller if there is limited food available to all salmon in the ocean. The abundance of phytoplankton, zooplankton and Pacific salmon vary temporally and spatially in offshore waters suggesting a top-down or predator related control of salmon production. Studies from 1991 to 1998 demonstrated that Pacific salmon mortality was in part due to high predation by salmon sharks (Lamna ditropis). Juvenile Pacific salmon are also vulnerable to predation by seabirds during their early marine life. Predation was higher in years when sea surface temperature was higher (1995 and 1998) than in years when it was lower (1996 and 1997). Japanese populations of chum salmon have a broader geographic range than North American populations because of the effects of western and eastern boundary current systems on factors such as larval drift or intra-species competition. Chum salmon distribution and abundance is also affected by sea surface temperature, although the linkages are not known. The average return rate of chum salmon was negatively correlated with sea surface temperature near the Kuril Islands and the central North Pacific after the mid 1960s but not before. Growth of chum salmon was positively correlated with sea surface temperature in the central North Pacific in the spring. After 1970, decreases in mean body weight, scale radius and scale width of the third year zones of age 4 chum salmon occurred. After 1976 there was an increase in mean age of Japanese chum salmon stocks. High seas surveys from 1972 to 1988 showed a negative relationship between Catch Per Unit Effort (CPUE) and mean body weight of chum salmon in the summer in the central North Pacific Ocean where Japanese and Russian stocks overlap. From 1979 to 1998 chum salmon CPUE increased and fork length decreased. Higher growth rates require greater demand for food intake which may lead to density dependant growth during peak growth seasons if prey is limited. This is particularly important as Asian chum salmon expend greater energy to migrate than other stocks during their first winter at sea because they swim northward against the southward wind-driven currents. No significant correlation was found between an index of Aleutian Low and CPUE and body size. The increase in CPUE in the late 1970s and early 1990s may be a result of shifts in the distribution of chum salmon caused by sea surface temperature changes related to the regime shifts in 1977 and 1989.

Korea

Korean fisheries resources were dramatically altered by the 1977 and 1989 regime shifts. The Aleutian Low and North Pacific High Pressure Systems changed, resulting in higher than normal sea surface temperatures and a northward shift in the thermal front. After the 1977 regime shift, volume transport of the warm Kuroshio Current increased and higher seawater and air temperatures were experienced until the 1998 regime shift. After the 1977 regime shift, an increase in the mixed layer depth resulted in decreased spring primary productivity and increased fall primary productivity. After 1989, primary productivity increased again with a significant increase in zooplankton biomass reported after 1991.

The return timing of chum salmon to Korean rivers changed from mid-November in the 1980s, to early November in the

1990s and late October in the 2000s. However, these changes have not been correlated with changes in local coastal and river water temperatures. The number of returning adults varied significantly from approximately 5,000 in 1984 to 20,000 in 1989. In 1990 there were over 100,000 returning chum salmon and these numbers increased to over 200,000 in 1996. From 2001 onward there was a steady return of between 40,000 and 60,000 chum salmon to Korean waters.

The increased recorded catch in the 1990s resulted, in part, from the inclusion of catches from set nets in the catch statistics which represented about 70% to 80% in the 1990s. The recorded catch dropped from 550 t in the mid-1990s to less than 200 t in the 2000s.

In 1984, 3 million juvenile chum salmon were released into the ocean around Korea. Releases increased to 10 million by 1990. Fish released between 1984 and 1986 had a return rate of less than 0.4%. The return rate increased to 1.0 – 1.5% for fish released between 1987 and 1995. In recent years the return rate dropped again to 0.2-0.3% for fish released from 1998-2000.

Between 1984 and 1998 scales were taken from returning chum salmon and used to determine the effects of climate and environmental change on the interannual variability of growth rates. In estuarine and coastal areas, growth rates of juvenile salmon were higher in the 1990s than in the 1980s. Early marine growth of juvenile salmon was related to sea surface temperature. Higher than normal spring/summer oceanic water temperatures (1-3°C higher) experienced between 1997 and 1999 may be a contributing factor to the increase in Korean chum salmon abundance during the 1990s, due to the corresponding increase in zooplankton biomass. The variability in salmon growth in the Bering Sea was correlated with an increase zooplankton biomass observed after the late 1980s which resulted in a period of good growth for juveniles in the 1990s. Bottom-up processes, controlling food availability to salmon, and sea surface temperature appear to be major factors affecting the growth and survival of juvenile chum salmon in the coastal areas of Korea. There is a decadal scale relationship with regimes that suggests a combination of natural (climatic) changes and anthropogenic (global warming) changes will affect chum salmon production. These changes will have more impact on Pacific salmon species in more southern latitudes, such as Korean chum salmon. If there is a general warming of the coastal areas, it is possible that marine survival will continue to decline even if fry production is maintained through hatcheries.

Russia

Trends in the abundance of Pacific salmon populations in Russia are associated with global climatic, oceanographic and ecosystem changes. Pink, chum and sockeye salmon are the most abundant species of Pacific salmon in the Russian Far East. In the last 15 years, the total biomass (including catch and escapement) has averaged about 340,000 t. The proportion of the total biomass of each species was 74%, 17%, and 7% for pink, chum and sockeye salmon, respectively. The increase in Pacific salmon abundance began in the late 1970s, but it has been most drastic since the late 1990s. Presently, Pacific salmon catches are at historic high levels in Russia. The total abundance of Pacific salmon in Russia has increased by 1.4 times since the 1970s and 1980s. This increase in abundance can be attributed mainly to the increase in pink salmon abundance (1.5 times), though the abundance of chum and sockeye salmon has also increased. Appreciable changes of chum salmon abundance have been observed in some regions. The total abundance of chum salmon off the north coast of the Sea of Okhotsk has approximately doubled. Abundances in the Amur River and on the Chukchi coast in west Kamchatka have decreased. Over the past 15 years, the total abundance of sockeye salmon on the east and west coasts of Kamchatka have increased by 1.5 and 1.9 times, respectively. At the same time, the abundance of coho and Chinook salmon has decreased by 1.5 and 1.9 times, respectively, possibly the result of poaching.

Pink salmon are the most abundant Pacific salmon species in the Russian commercial fishery, representing about 40% of the weight of all salmon and 60% of the numbers. The major production areas are in the Sakhalin Islands, along the east and west coast of Kamchatka and along the southern Kuril Islands. Presently, odd-year generations of pink salmon are dominant on the east coast of Kamchatka while even-year generations are dominant on the west coast. In Russia, as in other countries, pink salmon do not conduct long spawning migrations in fresh water. It is believed that the homing instinct is not as strong in pink salmon as for other species of salmon, with straying occurring for hundreds or even thousands of kilometres. Catches of pink salmon increased in the 1980s and 1990s and in recent years are at historic high levels. It is believed that pink salmon abundances follow natural trends in climate and that the current favourable trend will end soon. However, despite these forecasts, pink salmon returns continue to increase, indicating that ocean conditions remain favourable.

Chum salmon catches in Russia gradually decreased from the 1950s through to the 1970s. There was a gradual increase in catches in the 1980s followed by a decrease in the 1990s. In recent years, chum salmon catches have increased to levels about three times those in the 1970s. The average size of adult chum salmon is related to climate effects on the ocean, both on large- and regional-scales. The possibility of an interaction between hatchery and wild fish of the same species complicates any attempt to understand or forecast how a changing climate will affect future abundances.

Sockeye salmon catches in recent years averaged about 20-25,000 t which is approximately equal to the historic high catches reported in the 1920s to 1930s. Thus, the current ocean environment appears to be favourable for the production of sockeye salmon returning to the Russian coast.

The impact of climate on Pacific salmon production in Russia occurs during the winter in fresh water as a consequence of precipitation and air temperature changes. Warmer winters, in general, tend to favour improved fry production. Climate also affects Pacific salmon production in the ocean through large-scale atmospheric processes. Major trends or epochs in atmospheric circulation patterns affect the ocean currents that help govern zooplankton production in the major feeding areas of juvenile Pacific salmon. Interannual, decadal and long-term variability in climate have been recognized as major factors associated with changes in the production of prey for salmon. The detection of short-term and longer duration cycles is necessary to forecast future trends in Pacific salmon abundance. The effect of these natural cycles is large enough that they have more significant impacts than from greenhouse gas accumulations, likely until the mid 21st Century. Thus, there is an uncertainty among key Russian scientists that current or future warm epochs favourable for Pacific salmon production are associated with greenhouse gas accumulation. There is recognition of the importance of both natural cycles and of the possibility of an interaction between recent warming trends and these natural cycles. For example, cyclic changes in atmospheric processes over the Far Eastern Seas in the late 1990s were associated with a cooling of the ocean and increased ice formation in the winter. Thus, the effect of climate variation on Pacific salmon is well recognized, but it is recognized as a pattern that has occurred in the past and will continue into the future, with a possible additional impact of increased greenhouse gas concentrations.

Exact mechanisms of climatic changes that influence the biota are to a greater part weakly understood, especially because environmental processes may be detrimental for some species and favourable for others. Furthermore, even within the same "global epoch" neighbouring salmon populations may be characterized by different dynamics of their abundance and biological traits, according to the "Provinciality Law" (regional responses). As with global factors, exact mechanisms of regional influence remain unclear in most cases. External factors such as sedimentation (related to river discharge and winter ice cover) and temperature under certain types of atmospheric circulation are believed to influence significantly the reproduction rate of Pacific salmon. However, it is difficult and sometimes impossible to assess what factors affect salmon dynamics in the seas and in the ocean.

The mean body size has decreased in conjunction with recent high abundances of many Russian chum, sockeye, coho, and Chinook salmon populations. There is no clear relationship between body size and biomass of pink salmon populations from the Bering Sea, Sea of Japan and Sea of Okhotsk. One of the causes of recent changes in age and size of salmon in the North Pacific Ocean may be density dependence. The impacts of stock density are well-documented to affect Pacific salmon during their marine and oceanic forage period. However, variability in the size and growth rate of fish does not necessarily reflect the influence of density because these characters are not always dependent upon fish abundance rather upon the abundance, quality and availability of prey. Temperature and other oceanographic factors, as well as heredity may influence the metabolic processes of fish, including growth rate.

The change in biological characteristics and the mortality of Pacific salmon when abundance is high has been assessed in relation to the North Pacific carrying capacity. In this respect, much attention has been given to the competitive relationships between chum and pink salmon. There are some different opinions among Russian scientists on these relationships. Some scientists suggest that:

- the North Pacific carrying capacity has been surpassed for salmon stocks and that they will decline in abundance along with the productivity of hatchery chum salmon stocks;
- extremely high abundance of chum salmon has led to drastic rearrangements in the trophic structure of the North Pacific pelagic communities;
- pink salmon compete with chum salmon in most places of their shared habitat;
- chum salmon are forced to shift towards low-calorie prey (gelatinous species), which results in weakening of its skeletal musculature, other pathologic body changes and raised mortality.

According to other scientists, Pacific salmon do not overpopulate epipelagic ecosystems because of high food reserves in the Bering Sea, Sea of Okhotsk and the North Pacific Ocean. Interannual changes in food supply may affect some biological features (e.g. body size or growth rate), but it does not lead to a significant increase in Pacific salmon mortality. This opinion is corroborated by many papers on plankton and micronekton that are based on long-term data of marine research expeditions. The amount of food consumed by hatchery and wild salmon is, in general, much lower than the capacity of pelagic ecosystems to produce this food. According to some scientists, the biomass and production of zooplankton and especially macroplankton is frequently several times underestimated in modern-day publications. Though salmon species consume large amounts of food, especially during periods of high abundance, their role in trophic chains is far from being highly important. Even two- or three-fold variations in Pacific salmon abundance will hardly lead to significant changes in the structure of nekton communities. Many highly important nekton species (walleye pollock, sardine, Pacific herring, anchovy, mackerel, squids, etc.) regularly experience sharp variations in abundance, sometimes of one or two orders of magnitude, and their distributions are smaller than that of salmon. A number of observations support the idea that salmon stocks are below the North Pacific carrying capacity, and that salmon do not overpopulate epipelagic ecosystems.

Alaska

At present, catches of Pacific salmon are at historic high levels. Three species dominate the commercial catch in Alaska; pink (58% of total catch), sockeye (27% of total catch), and chum salmon (10% of total catch). Pacific salmon stocks have been impacted by both regional and large-scale climatic changes on interannual, interdecadal and longer time scales. In Bristol Bay, productivity is strongly related to fluctuations in climate and periods of good and bad years should be expected in the future. Due to the large geographic extent of Alaska, historic global climate shifts can result in differential regional effects. For example, a regime shift in 1977 affected Pacific salmon stocks throughout Alaska, while another shift in 1989 affected only stocks in western Alaska. Sockeye salmon in western and central Alaska were negatively impacted by a regime shift in 1947. The relationship between shifts in climate, the marine environment, and Alaskan sockeye salmon catches (low and high production regimes) resulted in low levels from the 1940s to 1970s (4.5 million caught in 1973) but record highs in the 1990s (> 64 million). Covariation in survival rates of Bristol Bay sockeye salmon may be due to a combination of both fresh water and marine processes. Environmental effects on survival rates of sockeye, chum and pink salmon act mainly on regional spatial scales rather than larger ocean basin scales. Regional regimes may mask, amplify or reverse the apparent larger scale changes.

The increase in abundance of Alaskan salmon populations in the late 1970s has been attributed to a number of factors including a change in management policies, elimination of high-seas driftnet fisheries, hatchery production, increases in fishing effort, warm seawater temperatures in the North Pacific, increased zooplankton productivity in the eastern subarctic Pacific and a regime shift to a positive PDO phase in 1977. The oscillating control hypothesis (OCH) predicts that salmon abundance in the Bering Sea increases during warm regimes as a result of greater prey abundance. This hypothesis is supported by evidence that warm regime dynamics in the eastern Bering Sea resulted in larger size and higher marine survival of juvenile sockeye salmon, possibly associated with increased abundance of forage fishes along the Bering Sea Shelf. Growth rates of sockeye salmon during the first and second marine year were highest when temperatures were warmer and abundances in the North Pacific Ocean were higher. At a larger Northeast Pacific Ocean scale, changing ocean and atmosphere conditions result in inverse production regimes in which conditions are more favourable for Alaskan and northern British Columbia sockeye, pink, and chum salmon and less favourable for U.S., west coast and southern British Columbia Chinook and coho salmon. Following the 1977 regime shift, sockeye salmon from Bristol Bay and Chignik River grew better in their first two years in the ocean, resulting in higher returns. Pink salmon that grew faster as juveniles experienced higher survivals. No difference in size between hatchery and wild fish was observed during years of higher survival, although wild juvenile salmon were significantly larger during years of lower survival, suggesting that wild fish may be more resilient to environmental stressors, or the occurrence of size-selective mortality of smaller fish earlier in the year.

Southeast Alaska is one of the state's most productive salmon areas, with over 2000 rivers contributing 47% of pink salmon catch, 61% of coho salmon catch, and 72% of the chum salmon catch. Hatchery production of chum salmon has nearly doubled the abundance of all chum salmon in recent years. In the early 21st Century, Southeast Alaska was experiencing record breaking catches, averaging 12.3 million Pacific salmon with 77% coming from hatcheries. Over 60 reports on the marine ecology juvenile salmonids from this area have been produced, but the factors that regulate production are still poorly understood. Implementation of a long-term research and monitoring program in southeast Alaska, using stock identification techniques such as genetics, thermal marking, coded-wire tags and data storage tags will result in a better understanding of migration patterns and timing, marine growth, carrying capacity, predation, and hatchery and wild interactions as well as the impact of climate change on these variables.

Pacific salmon abundance is related to ocean temperature both at the time of ocean entry and shortly before spawning. For sockeye and chum salmon, there was a positive correlation between warmer conditions at ocean entry and adult returns. Increases in abundance may have resulted in increased age at maturity and decreased mean size of returning adult chum salmon prior to the mid 1990s, but not after 1995 when body size at maturity increased, despite the high abundances. Pink salmon also experienced a decline in body size after the 1977 regime shift which persisted until about 1991 after which time body size began to increase again. Coho salmon from central and southeastern Alaska continued to decline in body size after the early 1980s. Pink salmon in Prince William Sound have increased in abundance but decreased in size in response to large scale enhancement that resulted in density-dependant growth in the Gulf of Alaska. Sockeye salmon in the Gulf of Alaska increased in abundance and decreased in size following an increase in sea surface temperature.

Warmer temperatures in the spring resulted in earlier ice breakup in southwestern Alaska. An associated increase in zooplankton abundances resulted in increased growth of juvenile sockeye salmon, suggesting that changing climate may enhance the growing conditions for juvenile sockeye salmon. Recent warmer temperatures also resulted in earlier spawning migrations, e.g., pink salmon in Auke Creek, Alaska. Associated earlier downstream migration could result in entry into the estuary prior to the spring bloom and consequently lower growth and survival. Alternatively, increased zooplankton abundance may reduce predation on juvenile pink salmon fry in Prince William Sound since predators will feed on common resources rather than searching specifically for alternative prey such as the pink salmon fry. Unfortunately, there is a lack of continuous long term data on prey abundance in the North Pacific, making it difficult to relate salmon abundance to prey abundance in changing regimes. Detecting and forecasting the effects of a changing climate is a major challenge that is complicated by the potentially confounding effects of density-dependence and differential responses of predators and prey. Continued monitoring of such mechanisms would help develop better understanding of how salmon-prey interactions affect the marine carrying capacity for Pacific salmon.

Growth and survival of Bristol Bay sockeye salmon in their second year in the ocean may be negatively impacted in odd-numbered years by the high abundance of pink salmon which results in decreased prey availability during the winter. These fish experienced 26% (age-2 smolt) and 45% (age-1 smolt) lower survival and 22% lower abundance than sockeye salmon interacting with pink salmon in the low abundance, even-numbered years. Evidence for competition between Alaskan sockeye salmon and Asian pink salmon highlights the need for multispecies, international management of wild and hatchery salmon production.

The Auke Bay Laboratory's Marine Ecosystem Stock Assessment Program BASIS group focuses on juvenile salmon research along the eastern Bering Sea Shelf. The objectives of this program are to understand juvenile migrations from the rivers to the eastern Bering Sea, to describe the physical environment of the eastern and northeastern Bering Sea Shelf waters and to collect biological information on other ecologically important species. Since the early marine period is a time of high mortality, coastal environmental conditions may be a key link between climate change and salmon abundance and the growth of juvenile Pacific salmon may be an excellent indicator of ecosystem change. Similarly, the size at maturity of chum salmon may be an indicator of ocean carrying capacity. Understanding these physical and biological parameters will provide insight into the relationship between Pacific salmon and their habitat. Understanding the mechanisms linking production to climate change will require continued long-term research and monitoring.

Hatcheries in Alaska produce about 800 million pink, 600 million chum, 60 million sockeye, 25 million coho and 10 million Chinook salmon every year. The central Alaskan hatcheries produce mostly pink and sockeye salmon while southeast Alaskan hatcheries produce mostly chum salmon. Prince William Sound alone supports more than 600 million hatchery and about 190 million wild pink salmon fry each year. Total pink salmon returns in this area averaged 31 million fish (25.3 million hatchery and 5.7 million wild) from 1990 to 2000. Hatchery fish are reared in pens during the spring and released into optimal feeding conditions when zooplankton abundances peak. The survival of hatchery reared pink salmon is dependent upon the duration of the bloom, the number of juveniles released, the size of the juvenile salmon at release and their growth rate. Up to 75% of all pink salmon fry rearing in Prince William Sound are lost to predation during the first 45-60 days in the marine ecosystem. Juvenile salmonids consumed only 1-3% of the available food resources in Prince William Sound. However, the average size of returning adults has declined and the productivity, expressed as returns per spawner, of wild stocks has decreased since the implementation of the large scale hatchery program. The interaction of these artificially produced individuals with wild stocks is poorly understood and there is difficulty in separating the effects of environmental and management influences on the success of these stocks. Long-term research and monitoring of interactions between hatchery and wild stocks, including longer temporal scales, would greatly benefit the management of all Pacific salmon stocks.

Washington, Oregon and California

Ocean-atmospheric climate variability over the North Pacific basin results in interannual and interdecadal changes which affect Pacific salmon survival. The abundance and survival of Pacific salmon from Washington, Oregon and California have been declining since the late 1970s. The effects of climate in freshwater and marine ecosystems such as the California Current are playing a significant role in this decline. Environmental variables such as sea level height, sea surface temperature, upwelling and wind stress affect different stages in the life cycle of Pacific salmon. Sea surface temperatures increased and coastal upwelling decreased resulting in reduced prey availability and poorer marine survival. Coastal upwelling has long been recognized as an important mechanism governing the production of both phytoplankton and zooplankton. It has also become apparent that the strength of the currents associated with this upwelling has a profound effect on the delivery of prey to predators or larval and juvenile fish to favourable feeding areas. Coastal upwelling affects individual growth and reproduction. Environmental effects impact both the early life history stages and adults just prior to spawning. Earlier maturation and larger size at return is explained by more rapid growth in the previous year. Chinook salmon escapements to the Klamath River between 1978 and 2005 were associated with environmental indices such as stream flow, coastal upwelling and large-scale ocean conditions. Marine survival of Snake River spring/summer Chinook salmon can be predicted using coastal ocean upwelling indices. A general additive model incorporates sensitive stages of Oregon coho salmon life history and environmental variables into a predictive model of marine survival called the Oregon Production Index. Forecasts using this model have been a successful part of local salmon management since the 1960s and its application to changing climate variables may be useful in forecasting more than one year in advance.

The Pacific Northwest Climate Index (PNI) incorporates temperature and precipitation trends to form an index of climate. This index can be used in management decisions for Pacific salmon. For example, when correlated to the PNI, higher catch and survival of Columbia River salmon are associated with a cool/wet climate and lower catch and survival are associated with a warm/dry climate.

Chinook salmon survival is correlated with ocean entry time and the timing of the spring transition. An optimal stability window hypothesis has been suggested to explain the physical and biological processes that cause the decadal variability demonstrated in variations in Pacific salmon abundance in the North Pacific Ocean. Water column stabilities resulting from weak or strong Aleutian Lows influence primary productivity. The stability window is a measurement of the balance of nutrients and light transmission that stimulates phytoplankton production. Coastal upwelling changes modify these factors and impact the marine survival of Chinook salmon. In order to ensure the future success, diversity of ocean- and stream-type Chinook salmon must be preserved. In regions where stream flow is dominated by snowmelt there is a higher proportion of stream-type individuals which are typically older fish that spawn earlier in the year. Climate change diminishes the capacity for snowmelt, thus limiting the habitat and genetic diversity of stream-type Chinook salmon.

Both marine and freshwater phases of coho salmon play a significant role in the variability of recruitment. In fresh water, air temperatures and second winter flows correlate strongly with smolt production. There is a relationship between air temperature and sea water temperature indicating that favourable freshwater conditions typically lend to favourable marine conditions. The majority (90%) of interannual variability in marine survival of hatchery reared coho salmon between 1985 and 1996 can be explained by coastal oceanographic conditions.

Changes in climate also affect the size of Pacific salmon produced in Washington, Oregon and California rivers. Size is negatively correlated with the multivariable El Niño Southern Oscillation Index (ENSO), resulting in smaller fish during El Niño events. El Niño years, which tend to be warmer and dryer, are associated with decreased snow pack, decreased stream flow and below average salmon survival. Warm conditions from 1950-1990 had a negative affect on coho and Chinook salmon production off the coast of Washington, Oregon and California. Cool/wet conditions did not show this relationship.

Hatchery reared juvenile Chinook salmon in Puget Sound released during even-numbered years demonstrate a dramatic decrease in survival (59%) when compared to those released in odd-numbered years. The impact of competition with pink salmon as well as climate effects after El Niño years are attributed to this decrease in survival. Furthermore, negative effects of hatchery salmon may be stronger on vulnerable populations. There is a strong negative relationship between wild Snake River spring Chinook salmon survival and the number of hatchery Chinook salmon released based on a 25 year time series. This relationship is accentuated during years of poor oceanic conditions in a changing climate.

Changes in ocean conditions appear to play a larger role in the survival of coho and Chinook salmon and steelhead trout in the Northeast Pacific ocean than does the increased production from hatcheries. For example, environmental and anthropogenic factors affect the spawning date of salmonids. Spawning dates for coho and Chinook salmon at the University of Washington hatchery have become earlier since the 1950s and 1960s in association with an increase in stream temperatures. However, genetic factors appear to play a more significant role in timing of spawning than stream temperatures. A model based on archaeological and paleological evidence was used to predict the effects of climate change on salmon populations from the Columbia River basin. The model predicts a 30-60% decline for these stocks under conditions similar to those 6000-7000 years ago when temperatures were up to 2°C warmer.

Changes in freshwater habitat quality, such as drought and temperature increases that affect California Chinook salmon, are a major concern. Mark recapture studies of 18 populations of threatened spring/summer Chinook salmon in the Salmon River basin in Idaho showed that fall stream flow was a good predictor of average survival. High temperatures (21-24°C as opposed to 13-16°C) result in decreased growth rates, impaired smoltification and greater vulnerability to predators. Habitat conditions mediate the effects of climate and possibly climate change which affect individual stocks differently. Coded wire tag data from 1971 to 1990 indicated that marine survival rates for coho salmon in the Pacific Northwest vary regionally.

Oregon's coho salmon are at critically low abundances due to freshwater habitat degradation and influences of decadal-scale climate related effects on oceanic survival. Coho salmon abundances cycle through good and poor survival regimes. Restoration efforts need to be supported in the long term with a greater understanding of climate variability within and spanning these regimes.

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