The Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River

February 2011

TECHNICAL REPORT 4

The Decline of Fraser River Sockeye Salmon *Oncorhynchus nerka* (Steller, 1743) in Relation to Marine Ecology

Stewart M. McKinnell, Enrique Curchitser, Cornelius Groot, Masahide Kaeriyama and Katherine W. Myers

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Preface

Fraser River sockeye salmon are vitally important for Canadians. Aboriginal and non-aboriginal communities depend on sockeye for their food, social, and ceremonial purposes; recreational pursuits; and livelihood needs. Fraser sockeye are key components of freshwater and marine aquatic ecosystems. Events over the past century have shown that the Fraser sockeye salmon resource is fragile and vulnerable to human impacts such as rock slides, industrial activities, anthropogenic-induced climatic change, fisheries policies and fishing. Fraser sockeye are also subject to natural environmental variations and population cycles that strongly influence survival and production.

In 2009, the decline of sockeye salmon stocks in the Fraser River in British Columbia led to the closure of the fishery for the third consecutive year, despite favourable pre-season estimates of the number of sockeye salmon expected to return to the river. The 2009 return marked a decline that could be traced back two decades. In November 2009, the Governor General in Council appointed Justice Bruce Cohen as a Commissioner under Part I of the *Inquiries Act* to investigate this decline of sockeye salmon in the Fraser River. In spite of the declining trend, in 2010 Fraser sockeye experienced an extraordinary rebound, demonstrating their capacity to produce at historic levels. The extreme year-to-year variability in Fraser sockeye returns bears directly on the scientific work of the Commission.

Seeking a better understanding of the factors that affect Fraser River sockeye salmon abundance, the Commission engaged independent experts to undertake 12 research projects:

Project	
1	Diseases and parasites
2	Effects of contaminants on Fraser River sockeye salmon
3	Fraser River freshwater ecology and status of sockeye Conservation Units
4	Marine ecology
5	Impacts of salmon farms on Fraser River sockeye salmon
6	Data synthesis and cumulative impact analysis
7	Fraser River sockeye fisheries harvesting and fisheries management
8	Effects of predators on Fraser River sockeye salmon
9	Effects of climate change on Fraser River sockeye salmon
10	Fraser River sockeye production dynamics
11	Fraser River sockeye salmon – status of DFO science and management
12	Sockeye habitat analysis in the Lower Fraser River and the Strait of Georgia

Researchers undertook the projects and analysed the contribution of their topic area to the decline in Fraser sockeye production. The researchers' draft reports were peer-reviewed and were finalized in early 2011. Reviewer comments are appended to the present report, one of the reports in the Cohen Commission Technical Report Series.

PICES Advisory Report on

The Decline of Fraser River Sockeye Salmon *Oncorhynchus nerka* (Steller, 1743) in Relation to Marine Ecology

December 15, 2010

North Pacific Marine Science Organization

PICES

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A Executive Summary

A major objective that was achieved in this report was to assemble, within an eight week period, as comprehensive a summary as was possible of what is known about Fraser River sockeye salmon (*Oncorhynchus nerka*) in the ocean. While much of this effort involved summarizing information published in data/technical reports and the primary literature, where necessary, original data have been re-examined and new analyses conducted to fulfill the terms of the Statement of Work. The compilation provides a background of knowledge against which to judge what can be known regarding the two major questions posed by the Cohen Commission to PICES:

Can the decline in Fraser sockeye in 2009 be explained by the conditions the fish experienced in the marine environment?

Is there any evidence for declines in marine productivity or changes in Fraser sockeye distribution that can be associated with the 15 year gradual decrease in Fraser sockeye productivity?

Most of the Fraser River sockeye salmon that did not survive to produce a fishery in 2009 entered salt water in 2007. The major challenge answering the first question was recognition that the ocean is shared by sockeye salmon from many areas of the Northeast Pacific, some which returned in 2009 in above average abundance. As a result, any hypothesis for the cause of low returns of Fraser River sockeye salmon from an oceanic cause must consider a mixture of contrasting observations:

- Double the average returns of Columbia River sockeye salmon in 2009 (2007 ocean entry year);
- Better than expected returns of Barkley Sound (West coast of Vancouver Island) sockeye salmon in 2009 (2007 ocean entry year);
- Very low returns of age-1.x ecotypes in most populations from the Fraser River that entered the ocean in 2007;
- Record high returns to the Harrison River (lower Fraser R. watershed) in 2010 from underyearlings that reared in the Strait of Georgia in 2007. This rather unique ecotype spends an extra year at sea, so its abundance was not known until 2010;
- Typical survival of acoustically-tagged hatchery-reared sockeye salmon from Cultus Lake northward through the Strait of Georgia in 2007.

Assessing the longer period of decline has its own challenges because impressions of the nature of the decline of Fraser River sockeye salmon are somewhat sensitive to how the production data are summarized. Our approach was to capitalize on the diversity and abundance of many reproductively isolated sockeye salmon populations, the existence of different ecotypes within each population (different ocean entry years by individuals of the same generation), and the lengthy time series of production data for many of these, to provide informative comparisons among populations and informative summary statistics across populations and ecotypes.

Long-term decline

1. What was described in the key question as a 15-year gradual decline in productivity bears a stronger resemblance to a shift to lower productivity in 12 of 16 stocks, rather than a gradual decline. In some stocks (e.g. Raft River), the data cannot distinguish between these two alternatives. The "best" division of a time series of median total survival of age-1.x ecotypes, into periods of high then low productivity is the 1992 ocean entry year (1990 brood year for age-1.x).
2. The 1992 ocean entry year coincides with an abrupt decline in marine survival of Rivers Inlet sockeye salmon. Markedly diminished returns to Long Lake (Smith Inlet) probably[i] began with the 1992 smolt year. These stocks share a common migration route through Queen Charlotte Strait/Sound.
3. Returns of maturing sockeye salmon to Barkley Sound declined in 1994 (1992 smolt year) and remained relatively low until the 1998/99 la Niña. A similar period of decline was observed in sockeye salmon returns to the Columbia River in the same year. West coast sockeye salmon production remained low from the 1992 ocean entry year through the 1997/98 el Niño, but then experienced an increase in survival that was not reflected in the Fraser River stocks. The difference could be related to variable spatial scales of the oceanic forces that are associated with variable survival among stocks.
4. The winter of 1991/92 was the onset of what has been called a persistent el Niño. The same year was accompanied by relatively dramatic changes in many characteristics of the West coast ocean ecosystem that included the return of sardines to the West coast of British Columbia after more than a 45 year absence. The reappearance of sardines is not considered as having a direct effect on Fraser River sockeye salmon survival, but is reported here as a potential proxy for a persistent oceanographic change that is not fully understood. British Columbia lies in the transition zone between the Alaska Current to the north and the California Current to the south, whose locations and intensities are variable.
5. Apart from the el Niño of that year, 1992 is not recognized especially as a year of significant large-scale climatic change in the North Pacific; that occurred in 1989. How or if the two phenomena are connected is not known at this time.
6. Productivity of the age-2.x ecotypes from the Fraser River did not change in 1992. This may be because larger postsmolts have greater energy reserves for the migration northward to better feeding and growth in Alaska.
7. Not all sockeye salmon that migrate from the Strait of Georgia exhibited a decline in 1992. The endangered Sakinaw Lake population from the mainland side of the Strait of Georgia

i Annual returns to the Docee fence include two brood years so the estimate of the decline is ±1 year.

(northwest of Vancouver) declined in 1987 rather than 1992; perhaps for other reasons. It may be related to greater use of Juan de Fuca Strait as their emigration route;.

8. Three years of very low returns of sockeye salmon to the Fraser River and curtailed fisheries from 2007 to 2009 can be explained by a sequence of independent events, two of them related to climate:
   a. 2007 returns: Low marine survival of the 2005 ocean entry year of sockeye salmon and coho salmon was expected (and was reflected in experimental forecasts). Canadian and U.S. oceanic and ecological indicators were consistent in recognizing 2005 as a warm and unproductive year which would likely be detrimental to salmon survival;
   b. 2008 returns: Median recruits per spawner across stocks were typical of the post-1992 era. The low return was most likely a consequence of one of the lowest numbers of spawners (in 2004) in recent years. Spawner abundance is the primary determinant of future returns in most Fraser River sockeye salmon populations.
   c. 2009 returns: The 2006/07 el Niño and a very anomalous spring/summer climate in 2007 conspired to generate a very atypical coastal ocean in 2007, one that could have been detrimental to Fraser River sockeye salmon growth and survival. The details are described more fully in the following section.

2009 returns

Biologists rarely observe death by natural causes of juvenile Fraser River sockeye salmon at sea. As a consequence, the cause and location of mortality must be inferred from general ecological/physiological principles that have been established by the scientific community. An example of one of these principles is that faster growth leads to better survival. It appears to hold across the salmonids and other families of fishes. No one saw the death of large numbers of juvenile Fraser River sockeye salmon in 2007, nor on the high seas from 2008–2009 so the best that can be done to understand the extremely low returns in 2009 is to identify the times and locations where there were extreme conditions that could potentially have caused the extremely low survival of one component of the Fraser River stocks. So the general hypothesis of this study is that there were no extremes [scientific hypotheses are disproved rather than proven] in ocean physics, chemistry, or biology that could have been responsible for extreme mortality of Fraser River sockeye salmon, but not elsewhere (Columbia River or Barkley Sound). At least one scenario suggests that this hypothesis can be rejected.

1. The low return of sockeye salmon to the Fraser River in 2009 was due mostly to high mortality of age-1.x ecotypes of the cohort that was spawned in 2005 and migrated to sea in 2007. When all returns of the 2005 brood year are eventually counted in 2010 and 2011, the lowest median total survival of Fraser River sockeye salmon in contemporary records is the 2003 brood year, not the 2005 brood year. While returns of the 2005 brood year in 2009 were very low, they are noteworthy mostly for their remarkable departure from the official equi-probable[ii] forecast, with one exception: Chilko Lake.
2. Since the 1960s, infrequent years of very high numbers of smolts emigrating from Chilko Lake, such as occurred in 2007 and again in 2008, have routinely failed to reach even average

ii Equal chance of getting more or less than this number.

postsmolt survival, suggesting that some fraction of the incremental mortality of this stock in the ocean is related to their own abundance. At 77 million, the emigration in 2007 was twice the previously observed maximum. The 2009 return year will be the lowest recorded age-1.x postsmolt survival for this stock.

3. Oceanic conditions with a strong potential to cause incremental sockeye salmon mortality began to develop from the effects of the el Niño of winter of 2006/07. The typical response of North Pacific climate to an el Niño is an intensification of cyclonic atmospheric circulation combined with an eastward shift in the storm tracks. This creates enhanced atmospheric flow from the Southwest that brings warmer, wetter air toward B.C. where it is deposited as snow in the mountain ranges. When winter ended in 2007, the northern and central coast mountains of B.C. had some of the highest snowpacks observed since records began in 1953.
4. The cool spring of 2007 delayed the snow melt. It was followed by rapid warming in late May which was followed by an intense spring storm in early June that brought heavy rain on top of the deep snow. As a consequence of these coincidences, the summer of 2007 featured extreme discharge by Central and North coast rivers. The northern part of the Fraser River drainage was exposed to this phenomenon but it led to high rather than extreme discharge in 2007. The highest weekly discharge in the Fraser River in 2007 ranked 23rd in the record of weekly discharges from records dating back to 1913. Discharges from the Wannock River into Rivers Inlet (eastern Queen Charlotte Sound) and the Klinaklini River (eastern Queen Charlotte Strait), for example, were the highest values ever recorded for the month of July.
5. A Fisheries and Ocean Canada (DFO) surveys in late June 2007 (and other years) across southern Queen Charlotte Sound, east of Triangle Island, recorded the lowest average surface salinity (five stations) since sampling began in 1998. Closer to the freshwater sources, the Egg Island lighthouse in eastern Queen Charlotte Sound recorded the lowest July/August average salinity on record (since 1970). The extreme freshwater discharge from coastal watersheds created an ocean surface layer in Queen Charlotte Sound that was much fresher than normal. This would have created a very stable water column (resistant to vertical mixing). Enhanced water column stability restricted the volume of water exposed to the overlying atmosphere in summer, and caused the surface ocean to warm more than it would have otherwise. Based on the NOAA (U.S. Government) global database from 1982 to 2010[iii], the only appearance of extreme sea surface temperatures in 2007 anywhere in the Gulf of Alaska in any month occurred at three grid points[iv] in Queen Charlotte Sound in August.
6. The relatively fresh ocean surface layer was retained within Queen Charlotte Sound by the most extreme southeasterly wind pattern in summer since 1948. Southeasterlies are normally considered as the winter wind regime. From April through July, May was the only month without much stronger than normal southeasterlies.
7. Fraser River sockeye salmon that were obligated to migrate through the Queen Charlotte Strait/Sound region met extreme temperatures[v], and even more extreme salinity/density and wind anomalies.
8. Since 1998, when SeaWiFS satellite ocean colour monitoring began, marine survival of Chilko Lake sockeye salmon has been highly correlated with the date of onset of biological production in Queen Charlotte Strait/Sound. The spring bloom in 2007 was the latest in the

iii The satellite remote sensing era.

iv Average monthly values are computed on a 1° × 1 ° lat./long. grid.

v Greater than any SST measurements recorded in that month from 1982–2010.

in record. No doubt the southeasterly wind regime in April contributed to the very late spring bloom in the Sound in 2007. The coastal migration of postsmolts from southern spawning habitats to northern feeding habitats (Southeast Alaska) requires sufficient energy for the migration. Energy for migration is a function of energy density leaving the Fraser River plus feeding success along the migration route. While the age-1.x postsmolts had poor survival in 2007, the larger age-2.x postsmolts, with their greater initial energy reserves, did not experience unusually low survival that year. The delayed spring in Queen Charlotte Strait/Sound, when combined with the incremental metabolic cost of migrating through a warm surface layer, with potentially lower prey densities in the fresher water, could be combined to reduce growth and survival. Sockeye salmon postsmolts caught in DFO summer surveys of Queen Charlotte Sound in 2007 had the smallest mean size since sampling began in the late 1990s. Where the growth reduction occurred along the migration route is unknown.

9. While the Gulf of Alaska was generally cool in 2007, the sockeye salmon migration route northward along the continental shelf region to Yakutat, Alaska had mean sea surface temperatures in August 2007 that were the second warmest since 1982, and feature the highest increase above spring sea surface temperatures since 1982, perhaps because the effect of the discharge anomalies was not restricted to Queen Charlotte Strait/Sound.
10. The extreme hydrographic and wind events that occurred in Queen Charlotte Sound/Strait during the summer of 2007 did not have equivalent extremes in the Strait of Georgia, nor on the West coast of Vancouver Island or the U.S. mainland. So, if the extreme mortality of age-1.x Fraser River sockeye salmon from the 2007 ocean entry year was caused by an equivalent oceanic extreme, the more likely location is Queen Charlotte Strait/Sound region where extremes in physics and biology were evident in 2007.
11. Fraser River sockeye salmon underyearlings (age-0.x) were found in high abundance in DFO surveys of the Strait of Georgia in September of 2007. These ecotypes returned in 2009/10 in unprecedented numbers to the Harrison River. If the Strait of Georgia was the sight of enhanced mortality in 2007, the unknown force(s) must have:
    1. killed most age-1.x ecotypes in May and June,
    2. allowed age-2.x ecotypes (Chilko) to have average marine survival,
    3. allowed age-0.x ecotypes to survive in record numbers, and
    4. allowed acoustically tagged hatchery-reared smolts (Cultus) to survive through the Strait of Georgia in 2007, as in other years,

…without observing extreme physical, chemical, or biological anomalies in the Strait of Georgia in 2007 that can be linked to sockeye salmon survival. Herring recruitment was observed to be low in the Strait of Georgia in 2007, but the lack of a long term association between herring and Fraser River sockeye salmon mortality suggests a coincidence. The harmful algae, *Heterosigma akashiwo*, bloomed in the southern Strait of Georgia for most of the spring and summer of 2007. It has been implicated as the causative agent for high mortality of the age-1.x ecotype[1] but it did not appear to affect the smaller age-0.x ecotype in that returned in record high abundance.

2010 returns

1. Age-1.x Fraser River sockeye salmon postsmolts migrated through a relatively warm surface layer of the Strait of Georgia in 2008 (not significantly different from temperatures in 2007) into a coastal ocean that was significantly colder and more Subarctic in character than had been seen on the B.C. coast in decades. Average summer temperatures in 2008 along the coastal migration route from Johnstone Strait northward were up to 3.5°C cooler in 2008 than in 2007. Annual average sea surface temperature in the Gulf of Alaska in 2008 was the coldest observed since the early 1970s.
2. The Mackas Ecosystem Productivity Index for the coastal ocean off the southwest coast of Vancouver Island reached its highest value on the "cool and productive" scale in 2008.
3. The numbers of effective female spawners in 2006 was the sixth highest since 1948, laying the foundation for a good return in 2010. Spawner abundance is the principal determinant of return abundance in Fraser River sockeye salmon.
4. Early signs of the bonanza that became the 2010 sockeye salmon return to the Fraser River were evident one year earlier in the returns of jack sockeye salmon in 2009 but there were few opportunities to notice their atypically high abundance. The appearance of relatively large numbers of jacks in 2009 in the seine test fisheries suggests that the abundance of the dominant cohort that returned in 2010 was determined before July of 2009.

B Fraser River Sockeye Salmon in the Ocean

1 Introduction

1.1 Motivation

Fisheries for Fraser River sockeye salmon were severely curtailed or eliminated for an unprecedented period of three years from 2007 to 2009. The low returns in 2009 attracted special attention because the pre-season forecast used by managers implied a harvestable surplus; one that never materialized. In Chilko Lake, for example, smolt-to-adult survival of the smolts that went sea in 2007 and will return from 2008 to 2011 may turn out to be, when all of the returns are counted, the lowest in the history of records that extend back to the 1950s. Most Fraser River sockeye salmon spend more than half of their lives in the sea[2] so any consideration of the cause of low abundance must take into account that the factors which are responsible for the decline may be found in salt water. A preliminary review of evidence implicated a marine cause for the poor returns[vi].

A related issue arose from an observation that the productivity of Fraser River sockeye salmon, measured as a ratio of aggregate adult returns to total spawners in all populations (Figure 1), has declined since the mid-1980s and may have reached its lowest level since the late 1940s in the 2007 ocean entry year. However, ascertaining whether or not this observation was solely marine in origin can be a challenge because returns per spawner are determined by factors affecting survival in both fresh and salt water. This issue can be examined using data from Chilko Lake where spawner to smolt, smolt to adult, and total survival (returns per spawner) have been estimated for many years.

While this report was being written in the summer of 2010, the largest return of Fraser River sockeye salmon since 1913 reached the British Columbia coast. Comments were requested by the Cohen Commission (hereinafter, the Commission) on the contrast with 2009 and previous years but an extensive analysis was not possible in the time allowed.

vi http://www.sfu.ca/cs/science/resources/adaptingtochange/FraserSockeyeThinkTankStatement.pdf

Figure 1: Ratio of aggregate (all stocks) sockeye salmon returns to the Fraser River to aggregate female spawners. Source: Pacific Salmon Commission.

1.2 Authorship – North Pacific Marine Science Organization

The North Pacific Marine Science Organization (PICES) is an international, intergovernmental marine science organization that was established by international convention in 1992 (Appendix 1). The current membership of the Organization includes Canada, Japan, People's Republic of China, Republic of Korea, Russian Federation, and the United States of America. They constitute all of the salmon-producing nations of the North Pacific except for North Korea.

The scientific committees of the Organization provide oversight of fisheries science, ocean/climate, biological oceanography, and marine environmental quality. The chairs of these committees and other expert groups form the Science Board that is responsible for the science conducted by the Organization. The PICES Science Board is responsible for the scientific products of the Organization, including general oversight of the development of this report.

1.3 Organization of the Report

A primary objective of this report is to provide the Commission with a review of what is known about the ecology of Fraser River sockeye salmon in the ocean. An historical approach was used so that an appreciation of what was learned, and when it was learned, can be ascertained. The basic material has been organized around three life-history stages that correspond roughly to the age of sockeye salmon at sea. Each stage is considered separately in Sections 2 to 4. Section 2 reviews the coastal migration of Fraser River sockeye salmon postsmolts[vii] and underyearlings through the Strait of Georgia and along

vii The definitions of terms used in this report can be found in Appendix 2.

the continental shelf. *Smolts* are juvenile sockeye salmon which have undergone the physiological changes to live in the ocean and have left the nursery lake where they have spent one or more years feeding and growing. This is to distinguish them from *underyearlings* which hatch and do not spend a winter in freshwater before entering the sea[2], however they may delay in sloughs and lagoons in the Fraser River delta[3]. The *postsmolt* stage is defined, arbitrarily, to begin with entry into saltwater and end with the calendar year when ocean entry occurred. The coastal migration of postsmolts begins in April and continues throughout the summer and fall as the cohort migrates seaward from the Fraser River.

Section 3 is concerned with the offshore feeding migration beyond the continental shelf of *immature* sockeye salmon. This stage is defined, again arbitrarily, to cover the period from January 1 of the calendar year after the postsmolt year to the December 31 of the year before they return to spawn. The final phase, in Section 4, deals with sexual maturation and homeward migration to a natal stream. These individuals will be designated in this report as *maturing* sockeye salmon, again arbitrarily defined from January 1 in the year when maturation occurs. The durations of each of the final two phases varies somewhat among individuals but, overall, a total ocean phase of about 25 months is the most common among sockeye salmon in the Fraser River. Jacks (and jills) which mature after the postsmolt year do not have an immature phase according to this definition.

While it was not possible to describe in detail every study that has been conducted, it was possible to touch on those expeditions that have resulted in significant improvements in understanding of Fraser River sockeye salmon. This perspective will provide a good background with which to compare any contemporary observations and provide the context for interpreting the questions of primary concern to the Commission. For the most part, the scientific history of Fraser River sockeye salmon can be determined by reviewing the results of publications that arose from each research project. However, some research programs produced data on Fraser River sockeye salmon for years but failed to produce data reports and/or failed to publish interpretations of the data. On those occasions when only the data were published, our approach was to analyze the data and report the results of those analyses. Likewise, if alternative interpretations of published results were possible, they were explored.

Because of the general lack of stage-specific estimates of mortality for the life-history stages described above, the overview of marine survival of all life-history stages was placed within Section 5. The physical, chemical, and biological oceanography and climate that were relevant to the periods of interest of the Commission were grouped in Section 6. Finally, Section 7 contains the discussion of the major questions posed by the Commission to the researchers.

This report deals with what is known about Fraser River sockeye salmon at sea, i.e. not all sockeye salmon. Where comparisons with other stocks help to provide a better perspective on the former, they have been made. In large part, this was necessary because the science of determining the origin of sockeye salmon caught at sea, with reasonable accuracy, has only recently been developed. The report excludes a consideration of the effects of toxins, parasitism, disease, and predation, as these topics are being considered in other reports to the Commission.

Readers must keep in mind that there is no observation system for Fraser River sockeye salmon on the high seas (beyond the continental shelf). Research and monitoring in the Strait of Georgia since 1997 has focused on coho salmon and chinook salmon in July and September after many sockeye salmon

postsmolts have left the area, and Fisheries and Oceans Canada (DFO) high seas salmon program has focused on postsmolt surveys on the continental shelf since the late 1990s, and is contributing to new understanding of this region[4]. Therefore, during the period of years of interest to the Commission, there are virtually no observations of Fraser River sockeye salmon during about 75% of their life at sea, and the value of coincidental samples taken during their emigration from the Strait of Georgia is debatable.

This discussion of the Commission's two key questions is restricted in scope to an examination of the interconnections between climate, the ocean, and the fish at each oceanic life-history stage; i.e. to what extent are "bottom-up" effects responsible for the status and trends of Fraser River sockeye salmon abundance. In simple terms, bottom-up forces are a result of the interplay of the physics, chemistry, and biology that provide for the growth and survival of sockeye salmon and other species at sea. For species that are resident on the west coast of British Columbia (not migratory), bottom-up forcing from year to year variations in phytoplankton at the base of the food web, through zooplankton production to fish production, has been reported[5].

1.4 Research Directed at Salmon in the Ocean

> *The scientists I have known upon the river, men as great as they are obscure, came almost to worship the salmon and hid their worship under scientific jargon. Watching the inscrutable quest of the salmon, recognizing a principle beyond their power to explain, these men (though they would be the first to deny it) turn into religionists of a queer, incommunicable congregation. The greatest of them, a man who had spent his life and genius on the study of these fishes, once said to me, as we watched them surge up the river: "We really don't know anything about them. I don't think we ever will."*
>
> Bruce Hutchison, The Fraser, 1950[viii]

Indeed, what the greatest of them (whoever s/he may have been) could not have anticipated was that one of the great unknowns, the whereabouts of Fraser River sockeye salmon at sea, would remain a mystery only until the mid-1950s when the newly formed scientific committees of the International North Pacific Fisheries Commission (INPFC) began their work. This tripartite Commission of Canada, Japan, and the United States was established in 1953 as a result of a clause in the San Francisco Peace Treaty that required it. In the 1930s, Japanese fishing fleets had been moving into the eastern Bering Sea to fish for salmon and the American and Canadian governments did not want fish stocks that they had been conserving to be exposed to unregulated fishing by Japanese fishermen. When the INPFC was established, financial resources were made available by the Government of Canada to its Fisheries Research Board to resolve the many uncertainties about the life of salmon at sea. Much of what is known today about salmon at sea was a consequence of the Board's contribution to the international research program. Ocean-going studies of salmon by Canadians were significantly reduced in scope after the late 1960s.

viii Bruce Hutchison (1901–1992) was Editor of the *Victoria Times* from 1950–1963 and the Editorial Director of the *Vancouver Sun* from 1963–1980; both are major newspapers in these cities.

One high seas study began in 1986 to investigate the potential exposure of salmon to large-scale squid driftnet fisheries[6, 7, 8]. The northern range of the target species, flying squid (*Ommastrephes bartrami*), was thought to overlap the southern end of the range of Pacific salmon. As a result, these surveys were directed at the southern fringe of the salmon distribution. The United Nations General Assembly declared a moratorium on large-scale driftnet fishing in the early 1990s; Canadian research cruises directed at the squid driftnet fishery ended in 1990.

Surveys to test a thermal limit hypothesis to describe the oceanic range of salmon in the Gulf of Alaska began in 1995[9]. After a few years of not catching salmon in the Gulf of Alaska beyond the continental shelf, it transformed into a successful coastal research program that, for the most part, focused on postsmolts and underyearlings in waters <200 m. As similar studies of juvenile salmon were being conducted in the United States, the coast-wide perspective, from California to Alaska, on postsmolt biology resulted in significant improvements in knowledge of this life history stage for all salmon species[4, 10, 11].

The first and most comprehensive review of the biology of sockeye salmon at sea was undertaken by the INPFC based on the results of its high seas research programme[12, 13, 14]. The first monograph on the sockeye salmon (in English) was published by the Fisheries Research Board of Canada[15] and reviews and compilations appeared intermittently thereafter[16, 17, 18]. Reviews directed at Fraser River sockeye salmon first appeared in the early 20th century as scientific interest developed around variations in the fishery and recovery from the Hell's Gate rock slide[19]. The most comprehensive overview of Fraser River sockeye salmon was undertaken by Roos[20] following the termination of the International Pacific Salmon Fisheries Commission, but it had a greater focus on the freshwater phases of sockeye salmon biology.

1.5 General Biology

There are seven species of Pacific salmon in British Columbia waters, namely sockeye salmon, pink salmon, chum salmon, coho salmon, chinook salmon, steelhead trout, and cutthroat trout, and all have anadromous ecotypes. They reproduce and incubate eggs in freshwater, move to salt water for a number of years to feed and grow, and then return to freshwater for spawning. Use of both the freshwater and oceanic environments implies important biological adaptations to each.

Fraser River sockeye salmon exhibit a diverse assemblage of life-histories[2]. Individuals can vary in age from a few months to a few years before migrating to sea. Once there, they can spend one to several years before maturing and migrating back to their natal stream. On average, the duration of the oceanic phase is shorter for males than for mature females because of the former's tendency for some faster growing individuals to mature at an earlier age. As a consequence of this variability, the members of a single cohort can be exposed to very different freshwater and oceanic environments depending on the year when they make the transition between these environments. This variability creates a bookkeeping challenge when comparing growth or survival or other aspects of biology to environmental variation. In general, the life-history of sockeye salmon is relatively plastic so the durations of these phases are not fixed within a population. In the Fraser River, the dominant ecotype matures following the second winter at sea (see Appendix 3 for proportions of ecotypes by population).

1.5.1 Life cycle of sockeye salmon

The life cycle of Pacific salmon consists of a number of discrete life history phases, including spawning, incubation, rearing, migration to sea of the juveniles, feeding and growing in the ocean, return migration to the home stream, upstream migration of mature adults, and spawning. After spawning all Pacific salmon die.

In North America, sockeye salmon are economically the most important Pacific salmon, with the most complicated life cycle. They lay eggs in nests dug in gravel beds in freshwater streams, rivers, and lakes. The juveniles then migrate to the ocean, feed actively, and grow rapidly. Upon reaching maturity, after one, two, or more years in the ocean, depending on the population, they return to their freshwater home-streams to spawn.

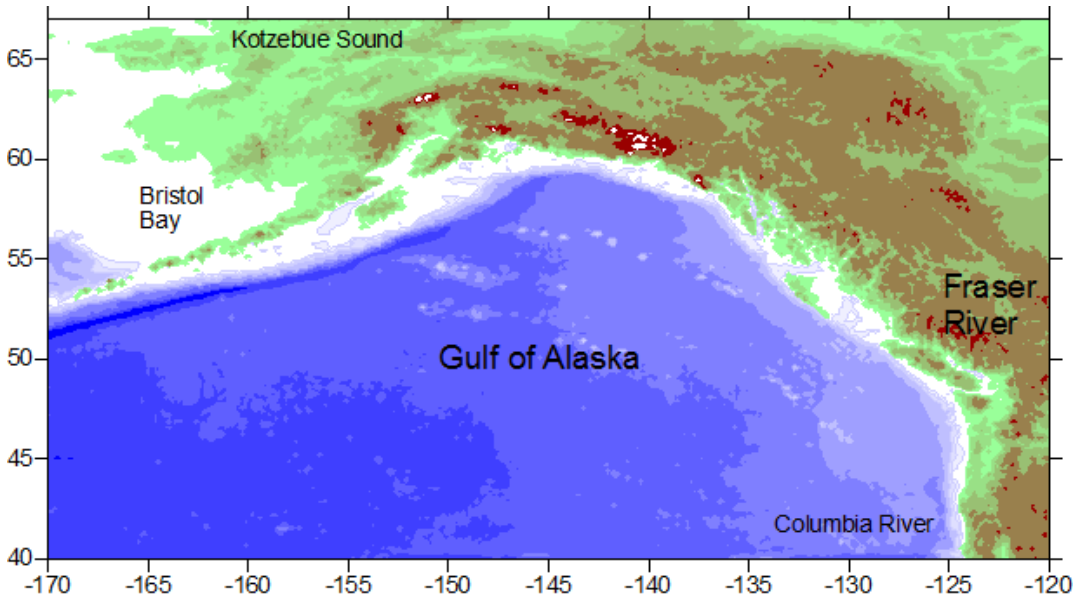

Figure 2: Range of sockeye salmon in North America from the Columbia River to Kotzebue Sound, with colour shading representing bathymetry/topography. The continental shelf appears in white.

The geographic distribution of sockeye salmon covers vast areas of the North Pacific Ocean and adjacent landmasses during their life cycle. The North American spawning distribution ranges from the Columbia River northward to Kotzebue Sound in Alaska (Figure 2), although during the last decade, they have been reported in the Arctic Ocean[21]. On the Asian side, sockeye populations are found from Cape Chaplina in the north, southward along eastern Kamchatka, the Kuril Islands to the north coast of Hokkaido, and then northward along west Kamchatka to the north coast of the Sea of Okhotsk. Some streams on the Komandorskiy Islands have small populations of sockeye salmon.

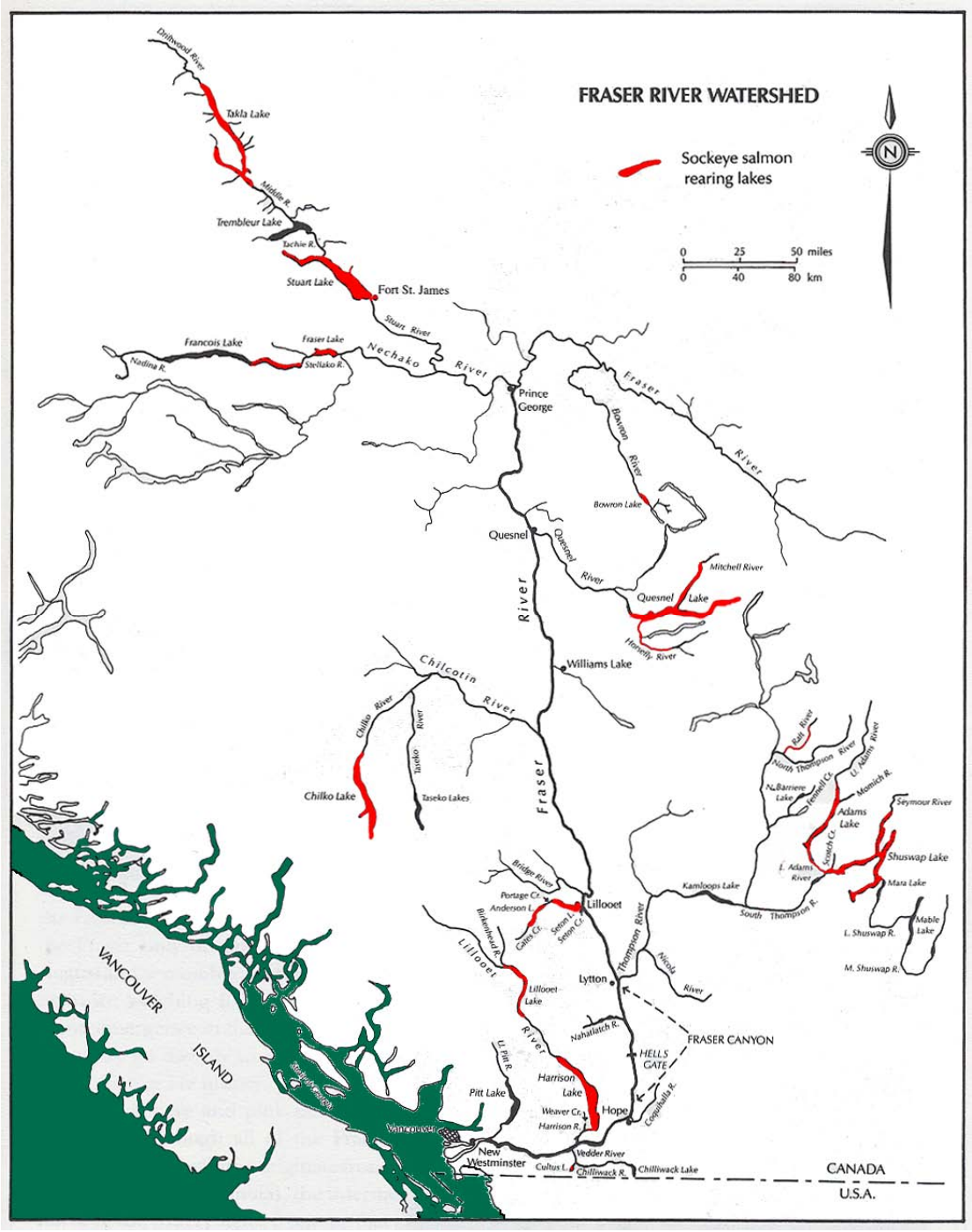

Figure 3: Sockeye salmon nursery lakes in the Fraser River watershed.

In British Columbia, the Fraser, Skeena, Nass, and Somass river systems are significant sockeye salmon watersheds. About 40 unique populations of sockeye salmon spawn in 22 lakes in the Fraser River watershed (Figure 3). Hereafter, one or more populations spawning in a specific lake will be referred

to as a stock. The Adams River stock is generally considered the most abundant although on average, the Chilko Lake stock has greater production because it does not exhibit the large interannual swings in abundance. Large sockeye salmon runs used to appear in Rivers and Smith inlets, where they spawned in tributaries of Owikeno and Long lakes, respectively. Despite their relatively small size, these two lakes had the highest production per unit area in the world. Great Central, Sprout, and Kennedy lakes are significant sockeye salmon nursery lakes along the West coast of Vancouver Island. In addition, there are many smaller lake systems supporting small sockeye populations.

1.5.2 Spawning behaviour

Spawning behaviour of sockeye salmon consists of a combination of nest building activities by the female and courtship displays by the male, leading to deposition of fertilized eggs in a nest. The female is the dominant partner in this process and interacts with both the gravel environment and the courting male in a specific sequence of activities. The activities include nest site selection, nest construction, courtship display, oviposition, fertilization, and closing of the nest. The female digs four to five separate nests in the gravel, one nest per day. Each nest contains several hundred eggs. After all the eggs have been deposited, the female covers all nests under a large gravel mound called a redd and defends the area against intruders. A few days after she has completed spawning, she dies and her body floats away with the current. This creates room on the spawning grounds for the next wave of ripe females to occupy nesting territories. The whole spawning process from moving onto the spawning grounds to death lasts about 10 days.

Unless indicated otherwise, quantitative references to spawner abundance in this report are *effective female spawners* rather than a total of males and females. The estimated numbers of female spawners is reduced in consideration of pre-spawning mortality, female fecundity, and percentage of eggs laid.

Salmon eggs develop in the gravel during the winter where they are protected from floods, ice conditions, and predators. The rate of egg development during incubation is dependent on water temperature and genetic characteristics related to environmental conditions of the specific population. Embryonic development is faster as temperature increases. For example, a 1°C difference in average incubation temperature can change emergence timing by four weeks.

A true larval stage does not exist in salmonids. When 10–20% of the yolk has been utilized, the alevin, a larva with a yolk-sac attached to its belly, hatches from the egg for further development in the protective gravel environment. When the yolk-sac has been absorbed, the young salmon, now called fry, emerge from the gravel in spring during the early hours of darkness within a narrow seasonal time window. Incubation, emergence, migration, and spawning are coupled and related to stream temperature and timed so that emergence of fry across stocks coincides with the development of plankton blooms in rivers, lakes, and the ocean. Differences in incubation temperatures between river systems are compensated for by changes in timing of spawning and differences in embryonic development rates. Fish that breed in relatively warm streams generally spawn later in the season, whereas those that breed in relatively cold streams, spawn earlier. The emergence time of fry is the major evolutionary influence that establishes spawning time. Fry from inlet streams will proceed downstream to a nursery lake whereas fry from lake outlets move towards the shorelines of the river and require a period of growth before migrating upstream to the nursery lake.

1.5.3 Migrations and habitat changes

In the nursery lake, most of the surviving juveniles rear for one year before making the physiological transformation that prepares them for the ocean. Their water type preference changes accordingly from freshwater to salt water and their colour changes from a yellowish brown fish with parr marks to one with silver sides and a greenish back. They are now called smolts and are ready to migrate downriver to the ocean.

Upon entering the Strait of Georgia, most sockeye salmon smolts turn northward and migrate primarily along the mainland shoreline. They exit the Strait of Georgia through channels among the islands and continue their migration through Johnstone and Queen Charlotte straits towards the North Pacific Ocean where they enter south of Haida Gwaii (Queen Charlotte Islands). Upon entering the North Pacific Ocean the postsmolts migrate north and westward in band within 35 km off the coasts of British Columbia and Central Alaska until they reach the overwintering grounds south of Alaska during late autumn and early December.

During their ocean residence sockeye salmon move relative to the annual temperature cycle in the Subarctic North Pacific Ocean. They are in waters colder than 7°C in winter, 10.5°C in spring, and 15°C in summer. Thus, they move south in spring and summer and north in autumn and winter. This migratory pattern is the reverse of birds which move north during spring and south in autumn during the changing seasons.

When sockeye salmon mature, they first migrate north from the ocean feeding grounds in late summer, then journey to the outlets of their home streams and rivers and continue to migrate upstream to the ancestral spawning grounds. The migration north and then towards the Fraser River is apparent from the changes in distribution of sockeye salmon captured and tagged in the North Pacific Ocean in April through August and recovered in fisheries that operate in the approach routes to the Fraser River around Vancouver Island.

Sockeye salmon enter the Strait of Georgia on their way to the Fraser River estuary by taking either the southern route via Juan de Fuca Strait or the northern route via Johnstone Strait. Up to 1977 about 80% of the sockeye salmon, on average, used the southern route. Thereafter, an increasing number (average 50%) of the Fraser River sockeye salmon entered the Strait of Georgia via the northern route. Although the cause of the change is not yet known, years of warmer sea surface temperature on the West coast of Vancouver Island resulted in more sockeye salmon using the northern route.
Upon reaching the Fraser River estuary, many sockeye salmon stocks continue their upstream journey to the spawning grounds (Figure 3). Some, like the Adams River population, may hold for up to three weeks off the Fraser River mouth before commencing migration upstream. The life cycle is completed by spawning and deposition of the eggs in gravel beds, and then death.

Thus, during their life cycle Pacific sockeye occupy a variety (12) of habitats (Figure 4). Each is like a bead in a chain linked together by migrations. Therefore, it is important that each habitat is in prime condition and that migration routes between them are not hindered or blocked or made unsuitable. Any weak or broken link will significantly affect production and survival of the salmon.

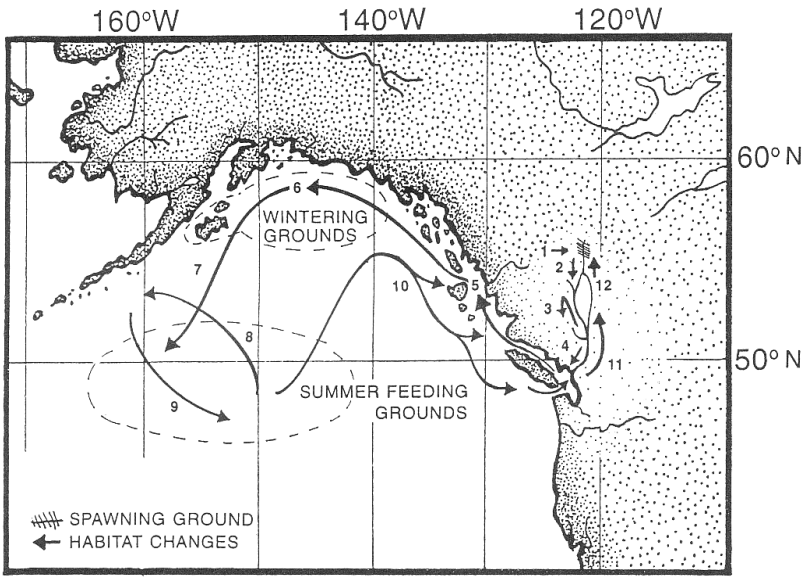

Figure 4: Habitats occupied by a typical Fraser River sockeye salmon.

The long distance migrations of sockeye salmon from habitat to habitat provide some of the most enduring puzzles in salmon ecology. The migrations are well timed and well directed and can vary from a few hundred metres to thousands of kilometres. To perform these feats, sockeye salmon possess a remarkable set of direction-finding mechanisms that include sun compass and magnetic compass orientation. They are also able to distinguish water masses, such as between their natal tributary and nearby tributaries, and differences between stocks on the basis of odour.

Sockeye salmon are also able to migrate to a goal, such as the estuary of their natal stream, from any area in the North Pacific Ocean. This goal-finding ability is evident in the high rate of homing (>95%) to their ancestral spawning grounds. To quote Ferris Neave, a fisheries biologist who worked at the Pacific Biological Station for many years, "*It is difficult to avoid the conclusion that throughout the period of ocean life some awareness of position in relation to the place of origin is maintained*". The mechanisms underlying this capability are not well known, except that learning of the characteristics of the goal is involved.

Despite an understanding of the migratory patterns of sockeye salmon and some of the mechanisms involved in direction and position finding and water recognition, we are unable to predict accurately certain key events that are critical to the management of harvests. The least well known of these are properties associated with their life at sea.

1.5.4 Ecotypes

The strong tendency of sockeye salmon to return to their place of birth for spawning resulted in geographic and reproductive isolation that led to the development of many ecological forms during evolution. Differences can occur in many aspects of their biology, such as incubation period, age of seaward migration of juveniles, size of juveniles at a given age, ocean distribution, route and timing of

migration shoreward, direction-finding abilities during migration, timing of stream entry, timing of spawning, fecundity, egg size and morphometric characteristics. These variations, which can vary both among as well as within stocks from region to region, are closely related to the ecosystems inhabited. There is sufficient evidence to conclude that many of the populations of sockeye salmon maintain such close associations with birthplace that they differ genetically from each other.

Many variations have developed in sockeye salmon upon the general pattern of movements between freshwater for rearing and reproduction and salt water habitats for feeding, by varying the duration of the juveniles in freshwater and of the immature in salt water from a few months to one or more years and by differences in timing of migratory patterns. Fry may move directly to salt water after emerging from the gravel; juveniles can spend two to three years in lake nursery areas before migrating to sea as smolts; maturing adults may return to their home river after one, two, or more years in the ocean; spawning can occur in inlet or outlet streams, along lake shores, or rivers. Also, the whole life cycle can be completed in freshwater as in the case of kokanee. In total, sockeye salmon have about 18 different ecotypes.

Throughout this report, different ecotypes are identified by their age (x.y) where x = the number of complete winters (from fall through spring) spent rearing in freshwater after hatching, and y = number of winters spent at sea. The most common type in the Fraser River is age-1.2. Where age-1.x appears, for example, it refers to all fish that emigrated as one-year-old smolts, regardless how many years they spent at sea. Likewise age-2.x refers to all two-year-old smolts, without regard for their return year.

1.5.5 Production cycles

The majority of sockeye salmon in the Fraser River drainage system mature in their fourth year. A fixed age at maturity provides little opportunity for significant genetic exchange among cohorts. This has resulted in distinct reproductive lines between years in many stocks. The rigid four-year life cycle of Fraser River sockeye salmon has resulted in four reproductive lines. One of the lines often greatly exceeds the other three in abundance and is called the “dominant line”. This phenomenon results in an imbalance in sockeye salmon population size in the Fraser River, producing a four-year cycle of abundance and catch. The dominant cycle often exceeds the others 100 to 1,000 fold.

In cases where strong cycles occur, elimination of a progeny line, by whatever cause, removes that line from the reproductive process and results in the loss of the genetic material of that particular year-class of a stock. Because of the inherited adaptations to the ecosystem, it may not be possible to easily restore lost populations of sockeye salmon in the event of natural or human-induced population failure. Many sockeye salmon stocks that disappeared from the Columbia and Fraser and other rivers never returned despite intensive restoration efforts.

2 Postsmolt Year

> *The author of Our Heritage of the Seas says "British Columbia salmon go to the Siberian shores and remain there until overcome with home-sickness, when they start back for the river of their birth. Others say that they only go out along the outer shores of our islands and there grow to maturity."*
>
> British Colonist, August 29, 1909

Population-specific studies of young Fraser River sockeye salmon during their first year at sea are rare because of the (historical) problem of identifying the origin of individual fish. While it is certainly possible that, of all sockeye salmon postsmolts sampled in the Strait of Georgia, some were from other stocks in the Salish Sea (e.g. Sakinaw L., L. Washington), we consider this probability to be relatively low because of the dominance of production from the Fraser River, and do not consider it further.

2.1 Postsmolt Migration Route

> *"After leaving the rivers, no young sockeyes are on record from salt water along the BC coast. The young of all other salmon species can be caught in traps in Juan de Fuca strait; the sockeye must pursue a different course."*
>
> C.H. Gilbert, 1914

The first reference to postsmolt migration routes from the Strait of Georgia was made by Charles Henry Gilbert[2]. The coastal trap was a common method of fishing for salmon in B.C. in the early 20th century. Operators of these traps in Juan de Fuca Strait reported that they did not find sockeye salmon postsmolts in their traps, although other salmon species were found. A similar result was reported following a summer of sampling in the San Juan Islands. W.A. Clemens (UBC) was teaching at the University of Washington's Friday Harbor laboratory on San Juan Island (between Washington State and Vancouver Island) during the summer of 1950. Using a beach seine, he caught no sockeye salmon postsmolts that summer. As he concluded that he must have missed their outmigration by sampling in July and August, it appears that he expected to find them emigrating via Juan de Fuca Strait.

The first significant study of Fraser River postsmolt biology in the Strait of Georgia was conducted by the Fisheries Research Board of Canada from 1966–1969 using a surface trawl net that was towed between two boats[22, 23, 24, 25, 26, 27, 28, 29]. Previous experimental fishing at different depths had shown that the greatest concentration of fry and postsmolts was found in the upper 3 m of the water column in this region[30]. Sampling that occurred in 1973 and 1975 was either brief (1973) or in different locations from the main investigation (1975)[31]. This investigation had a multi-trophic-level ecological perspective that was novel for the era[32, 33, 34]. The focus of the study was the Fraser River plume (Figure 5). Fieldwork included sampling juvenile salmonids and other fishes, their diets, and the prey field during spring and summer. The intensity of sampling was approximately monthly but varied from year to year with 1968 providing the most comprehensive sampling frequency because of additional sampling in Saanich Inlet.

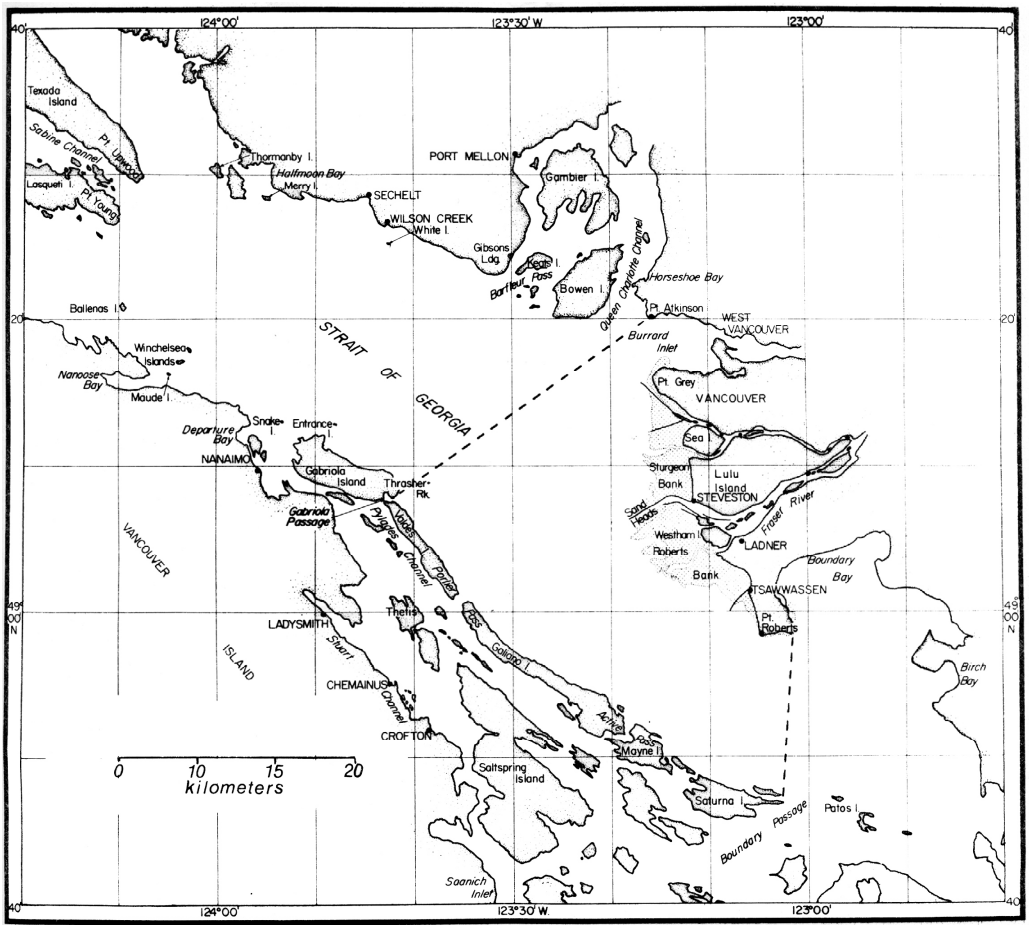

Figure 5: Map of the Strait of Georgia showing the survey area between the dashed lines. Copied from Barraclough and Phillips[30] (1978).

While the study was not designed to identify migration routes, a conclusion drawn from this investigation was that salmon from the Fraser River migrated in a southwesterly direction toward the Gulf Islands.

> *"Young migrating salmon, in part directed by these currents, move across the Strait of Georgia, and through Active and Porlier passes and along the shores of Vancouver Island and the Gulf Islands where they may occupy nearshore areas temporarily before continuing through the Strait of Juan de Fuca [sic] to the open Pacific by late summer."*
>
> Barraclough and Phillips, 1978

In the summer of 1968, U.S. sampling under the auspices of the INPFC, of a three-station transect across Juan de Fuca Strait using a seine net took a total of only 54 sockeye salmon postsmolts in 37 seine samples collected from June 23 to July 17 and 13 sets collected from August 11 to 23[35]. Of the five species caught, sockeye salmon was the least abundant. Of the few that were caught, most were taken in the July sampling on the Vancouver Island side of the strait, but because so few were caught, the authors felt that the June–July sampling in Juan de Fuca Strait had missed the sockeye salmon postsmolt outmigration. If this was true, the sockeye salmon postsmolt migration would have reached the west coast of Vancouver Island before June 23. This bit of logic does not agree with their general observation for the period April–June, described in a different part of the report, that "*juvenile sockeye salmon were just beginning to enter the open ocean in late June.*"

In the mid-1970s, research on juvenile salmon ecology in the Strait of Georgia was continued by Dr. Michael Healey, then of the Department of Fisheries and the Environment. A review of this and previous studies in the Strait of Georgia led Healey to think that most juvenile sockeye salmon left the Strait of Georgia via the Gulf Islands and Juan de Fuca Strait[36]. He also made note of underyearling sockeye salmon (age 0.x) accompanying the smolt migration downstream in the Fraser River[36]. A study of Deas Slough, located 10 km upstream from the mouth of the Fraser River, in 1976 and 1977 found age-0.x migrants in abundance in 1976 and 1977[3]. They were the most abundant salmonid and the fifth most abundant fish species caught in beach seine nets. The mean length of the underyearlings was ~30 mm when sampling began in April and May. By summer, the underyearlings had grown to a mean size of 60–80 mm in the slough and were approximately the same size as age-1.x sockeye smolts[3]. After migrating to sea, age-0.x sockeye salmon remained in the Strait of Georgia in August and September to allow them to reach a larger size before emigrating to the West coast[36].

The next study in the Strait of Georgia, and one that focused on understanding Fraser River sockeye salmon postsmolt migration, was conducted by Dr. Kees Groot (Pacific Biological Station) from 1982–1984. As late as 1980, at least some scientists at the Pacific Biological Station thought that Fraser River sockeye salmon postsmolts left for the open sea via Juan de Fuca Strait [30, 36]. In 1978, when the proportion of adult Fraser River sockeye salmon taking the northern route via Johnstone Strait increased substantially,[37, 38] it inspired an hypothesis that maturing Fraser River sockeye salmon were returning to the Strait of Georgia via the route that they had used as postsmolts to emigrate seaward[39]. Several years of sampling in the region confirmed an idea, first inferred in 1913, that sockeye salmon postsmolts tend to leave the Strait of Georgia via Johnstone Strait[2]. Groot and Cooke[39] found that Fraser River sockeye salmon postsmolts used two main routes during their migration through the Strait of Georgia (Figure 6). One tracked along the eastern shore and one followed through the Gulf Islands and the western shore before migrating across the strait to the eastern shore.

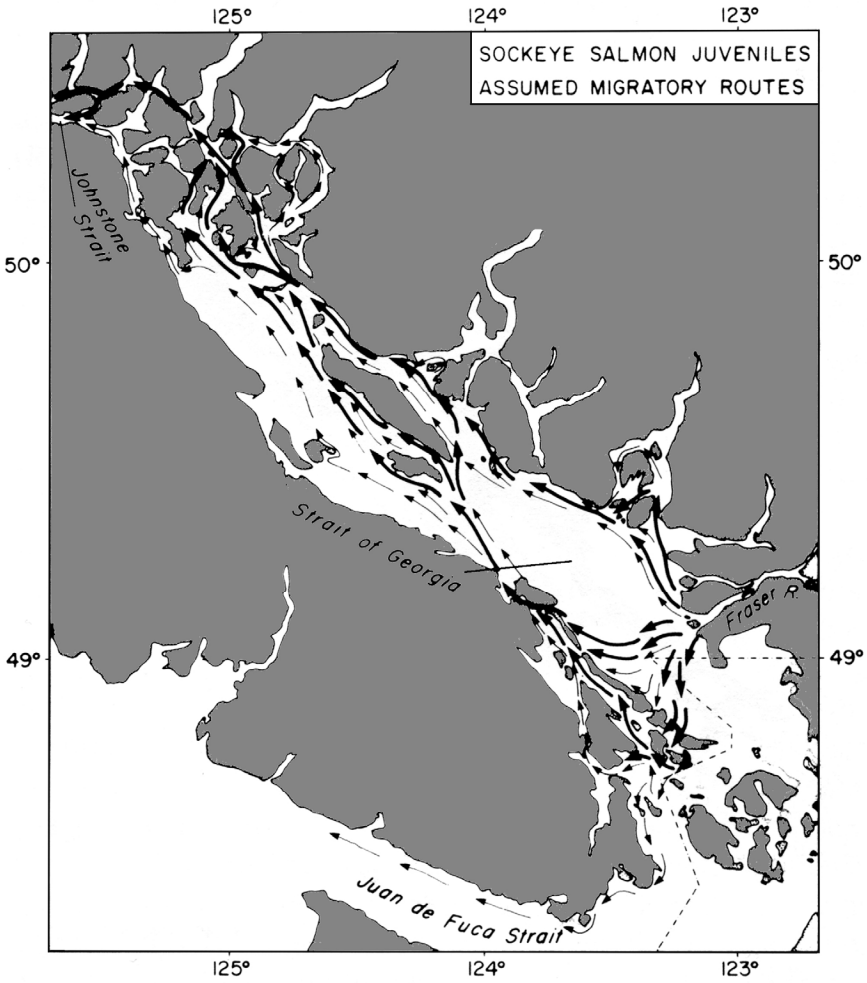

Figure 6: Assumed migration routes of Fraser River sockeye salmon postsmolts based on surveys conducted from 1982–1984. Adapted from Groot and Cooke[39] (1987).

A contemporary multi-year acoustic tagging study of hatchery-reared Cultus Lake sockeye salmon migration in the 2000s has shown that Johnstone Strait is not used exclusively as the route of emigration by this population[40]. Four percent of detections from 2004–2007 occurred at southern locations. Most (> 90%) of the acoustically tagged postsmolts from Cultus Lake, with their surgically implanted tags, headed up the Strait and most of these left relatively quickly via that route[40].

Since the mid-1990s, trawl surveys for juvenile salmon have been conducted routinely by various agencies along the North American coast[41]. For the most part, these surveys confirmed the Hartt and Dell[35] idea of a counterclockwise migration of postsmolts along the continental shelf. Migration was inferred from seasonally changing patterns of abundance in the trawls, with sockeye salmon showing the strongest north–westward shifts in relative abundance throughout the postsmolt migration season[41]. There are always exceptions. A mid-water trawl survey in Hecate Strait in November 1963[42] found a small number of sockeye salmon postsmolts at depth. They ranged in fork length from 168–198 mm and in weight from 50–90 g[43, 44, 45, 46, 47].

The most recent review of Fraser River sockeye salmon postsmolt migration behaviour was developed from observations made during coastal trawl sampling from 1996 to 2007[10]. In total, across all years, the proportion of Fraser River sockeye salmon caught among the 4,062 sockeye salmon individuals taken from May to February was 0.42. From the spatial and temporal patterns of the composite catch (all years combined), the study found that, after leaving the Strait of Georgia, most of the postsmolts, identified by DNA as Fraser River sockeye salmon, were located north of Vancouver Island in May and June rather than on the West coast of Vancouver Island. They interpreted this finding as evidence of a Johnstone Strait migration route to the open sea.

From Queen Charlotte Sound, most postsmolts migrated rapidly into northern British Columbia and Southeast Alaska (Figure 7) via Hecate Strait[10]. This migration route was inferred from lesser catches of Fraser River sockeye salmon postsmolts on the west coast of Haida Gwaii. Catches of Fraser River sockeye salmon postsmolts in summer (July–August) were highest in central B.C. (Queen Charlotte Sound and southern Hecate Strait). They noted that sockeye salmon postsmolts from the Stuart Lake and Stellako River populations were not found in catches in central B.C. by the fall whereas other populations were found there. From this, they inferred a different migration pattern with offshore migration occurring earlier than the other northward migrants. Winter sampling along the West coast produced much lower catches. A noteworthy feature of winter surveys was the appearance of Harrison River sockeye salmon along the West coast of Vancouver Island. From this observation, they inferred that Harrison River sockeye salmon migrated from the Strait of Georgia via Juan de Fuca Strait. Furthermore, winter was the only season when Harrison River sockeye salmon were caught. It is noteworthy, however, that some Fraser River sockeye salmon (other than Harrison fish) were present in July samples, suggesting that some proportions of other stocks migrate via Juan de Fuca Strait in some years.

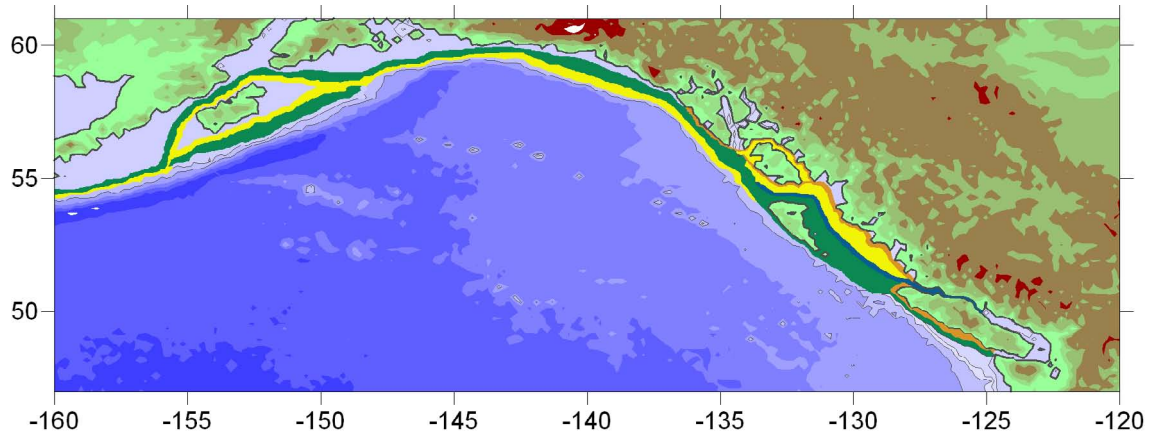

Figure 7: Seasonal migration of Fraser River sockeye salmon postsmolts after leaving the Strait of Georgia (blue: May–June, green: July–August, yellow: October–November, orange: February–March, based on Tucker et al.[10] 2009 (their Figure 5c). N.B. Relative amounts of colour are intended to reflect relative seasonal abundances at various locations along the coast rather than specific migration pathways (i.e. Fraser River sockeye salmon do not migrate solely in the centre of Queen Charlotte Sound/Hecate Strait but are found in this region in lower abundance than in July–August and October–November).

Coastal trawling for juvenile sockeye salmon from 1996–2007[10] confirmed previous conclusions that sockeye salmon postsmolts followed a northward and westward migration along the continental shelf[35]. The novel contributions of the recent surveys were made possible by the development and application of DNA stock identification to provide new information on stock-specific migration patterns. Unfortunately, annual differences and similarities in migration routes were not possible to identify because the numbers of sockeye salmon obtained from the trawl surveys were too few[10].

Summary – The first idea about the route taken by sockeye salmon postsmolts from the Strait of Georgia was based on their rarity in fish traps in Juan de Fuca Strait[2]. The juveniles of all other species of Pacific salmon were found there, but not sockeye salmon. This observation (all species but sockeye salmon) was repeated in July 1950 during beach seining in the San Juan Islands[48]. Scientific investigations in the 1960s and 1970s reported that sockeye salmon postsmolts left the Strait of Georgia via the Gulf Islands and Juan de Fuca Strait[30, 36] although sampling at the western entrance to the Juan de Fuca Strait in 1968 failed to find any abundance of them in June, July or August[35]. Intensive sampling (both spatially and temporally) for several years in the Strait of Georgia in the early 1980s found that most Fraser River sockeye salmon postsmolts were migrating from the Strait of Georgia via Johnstone Strait, including at least some of those found among the Gulf Islands. In the 2000s, acoustic tagging and stationary detection lines confirmed what Groot and Cooke had described[40]. While it is possible that the major migration route from the Strait of Georgia to the coastal ocean changed from Juan de Fuca Strait before the 1980s to Johnstone Strait from the 1980–2000s, the low abundance of sockeye salmon postsmolts found in the Juan de Fuca Strait in May through July in all sampling efforts suggests that they may have always used Johnstone Strait as the main pathway.

2.2 Postsmolt Migration Timing

Since 1997, the date of 50% emigration of Chilko Lake smolts from the lake has a range of 13 days (Figure 8). The earliest peak date observed since 1997 was April 26 (2005) and the latest peak date was in 2003 (May 9) and there is no trend apparent. In 2007, the largest recorded smolt run had an intermediate emigration date of May 2, one day earlier than the average for this period. As flows in the Fraser River were higher than average during 2007, it is not unreasonable to assume that Chilko Lake smolts may have arrived at the Fraser River estuary no later than the average date of their arrival.

Acoustic tagging of age-2.x smolts as they left Chilko Lake in 2010 confirmed earlier thoughts about the duration of the migration from Chilko Lake to the Strait of Georgia. Preliminary results of the migration of tagged fish indicated that the average time spent in rivers was eight days, with the earliest tagged fish arriving in four days and the latest fish arriving after 18 days[49]. If applied to the 2007 emigration from Chilko Lake, the peak would have reached the Strait of Georgia on May 10. As flows were higher in 2007 than in 2010, arrival times in the Strait of Georgia may have been earlier. Applying the best estimates of migration time through the Strait of Georgia to these dates would easily place the Chilko Lake postsmolt migration in Johnstone Strait by the middle to end of June.

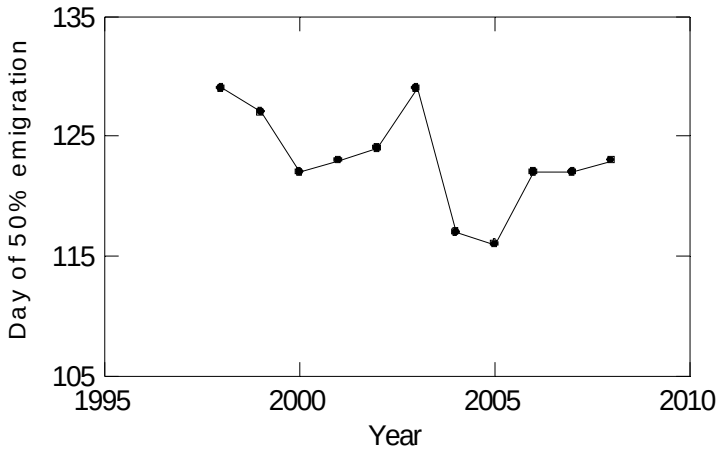

Figure 8: Day of year, 1998–2008, when 50% of the smolt run passed the Chilko Lake smolt fence.

From 1966 to 1969, sockeye salmon postsmolts from the Fraser River did not appear in the samples in the southeastern Strait of Georgia until late April when their abundance increased abruptly[30]. The sockeye salmon were described as spending the least amount of time in the open waters of southern the Strait of Georgia. High abundance compared to other species of salmon, in the clear saline waters of Porlier Pass and Active Pass was interpreted as an ability by sockeye salmon for rapid adaptation to the marine environment[30]. Their general abundance in the samples was described as less than pink and chum salmon, uniform through May, and slightly higher in June and July, with considerable year to year variation[30].

While the surveys in the 1960s were not intended to determine sockeye salmon migration timing or routes, some patterns can be inferred from the changing relative abundances. A total of 785 sockeye salmon postsmolts was caught in the Strait of Georgia during these four years of sampling, with 85% taken by the end of June. The percentage of all sockeye salmon postsmolts that was collected in July varied annually from 4.9% to a high of 43% in 1967 (annual average, 14%). Those taken in July of 1967 had the smallest mean length (65 mm) of any monthly averages during the study (Figure 9). As salmon are not known to shrink in length, an observation of smaller mean size suggests a different population composition of the samples as the season progressed. These individuals had the approximate mean size of age-0.x sockeye salmon that Birtwell et al.[3] reported from Deas Slough. The only source population with high proportions of small underyearlings is the Harrison River. Samples of sockeye salmon collected in May 1967 suggest the presence of underyearlings (~40 mm) in the Strait of Georgia that month.

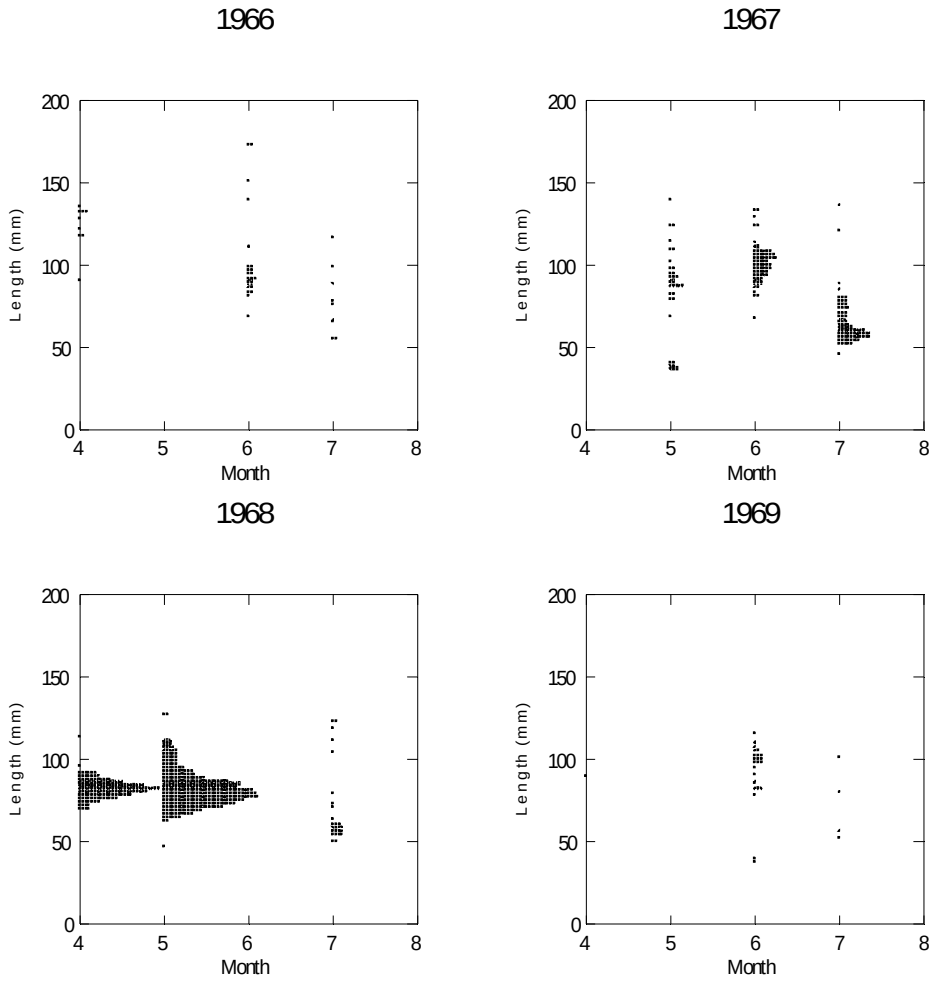

Figure 9: Length frequency distributions of sockeye salmon taken in two boat surface trawls in the Strait of Georgia from 1966 to 1969. The overall declining trend in mean length in each year is a result of the seasonally changing composition of the samples, not negative growth. Each year includes three length frequency modes – underyearlings, age-1.x postsmolts, and age-2.x postsmolts. April of 1966 is mostly age-2.x postsmolts while April 1968 is mostly age-1.x postsmolts. May of 1967 included some underyearlings.

Sampling with a purse seine in the Gulf Islands from May to October of 1976 found the highest juvenile sockeye salmon catches in May and June[36]. By July, the average catch per set was only 20% of what was caught in May and June (Figure 10) and the maximum number caught in a set had declined from 102 to 15 in May and 53 in June. Fishing locations during this study were predetermined rather than adjusted according to what had been caught in previous sets. Based on the patterns of catch in the Fraser plume and the Gulf Islands,[36] Healey estimated that sockeye salmon postsmolts took 20–30 days to pass from the Strait of Georgia, but this estimate was developed with a Juan de Fuca Strait migration route in mind.

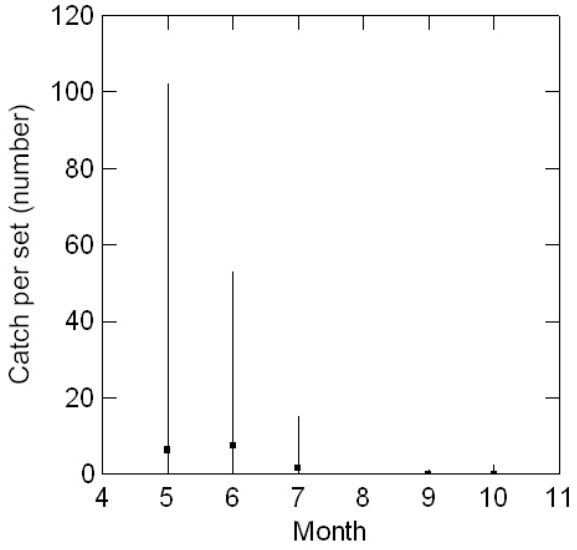

Figure 10: Average numbers of juvenile sockeye salmon caught per set (solid squares) and range of numbers caught per set (vertical lines) around the Gulf Islands, May to October 1976. At least 40 sets occurred in each month except July (n = 26).

Extensive fine-mesh seine sampling from Washington State (Cape Flattery) northward to the Aleutian Island chain, under the auspices of the INPFC, led to the conclusion that...

> *"by the month of July, juvenile sockeye salmon were present in substantial numbers in coastal waters adjacent to most major production areas, showing that their oceanic embarkation was well underway."*[35]

This conclusion was reached after examining 3,073 purse seine sets taken from throughout the Northeast Pacific Ocean, Bering Sea and Aleutian archipelago from 1956 to 1970, although specific efforts directed at juvenile salmon occurred from 1964 to 1968. Prior to July, sockeye salmon postsmolts were found only off the west coast of Vancouver Island and on the continental shelf near Sitka, Alaska[14]. By August, the overall range of locations where sockeye salmon postsmolts was found was similar to July but the relative abundance was diminished in the south off Juan de Fuca Strait and the west coast of Vancouver Island and increased in the northern Gulf of Alaska. By September and October, the range remained similar to that found in August but catches were significantly diminished in the eastern and southern Gulf of Alaska. Despite extensive offshore fishing with fine-mesh a purse seine from 1956 to 1970, sockeye salmon postsmolts were not found in the deeper waters of the Gulf of Alaska[14].

Trawl surveys in July and September in the Strait of Georgia from 1997 to 2002 caught a total of 117,571 juvenile salmon of pink, chum, coho, and chinook[50]. It was not possible to include sockeye salmon in the analysis because comparisons among years were complicated by spending less time in the Strait of Georgia compared to other species[50].

2.3 Postsmolt Migration Speed

Rates of migration of individual sockeye salmon from the Fraser River are reported infrequently. Generally, estimates of migration rates are inferred from the changing spatial patterns of sockeye salmon distribution in surveys. Using this approach, Groot and Cooke[39] reported that, after three years of field studies, it appeared that Fraser River sockeye salmon postsmolts moved through the Strait of Georgia in about one month. Acoustically-tagged hatchery-reared sockeye salmon smolts from Cultus Lake had average residence times in the Strait of Georgia from 25.6 to 34.1 days, computed from four years of tagging studies from 2004 to 2007[40]. These results may not reflect migration speed of the general population, however, as the average size of the tagged sockeye salmon smolts from Cultus Lake (159–189 mm) was nearly double the average size of a wild sockeye salmon smolt (~88 mm)[51]. The acoustic tags confirmed that most of these postsmolts used the eastern route of Groot and Cooke[39]. A diffusion model of the downstream migration of Chilko L. sockeye salmon smolts[52] forced by 1984 environmental conditions placed all Chilko Lake postsmolts in the Strait of Georgia by the end of May[53].

Millions of coded wire tags have been applied to juvenile Pacific salmon but rarely were they used to study wild sockeye salmon. In rare recoveries of three coded wire tagged sockeye salmon postsmolts from the endangered Redfish Lake (elev. 1996 m) sockeye salmon population, Tucker et al. [10] reported that their average migration speed from the lake in Idaho to the recovery location along the British Columbia coast varied from a low of 40 to 48 km d^{-1} during the 45 to 55 days at large. If these migration speeds are applied to the route travelled by most Fraser River sockeye salmon postsmolts, assuming a directed migration toward Johnstone Strait, they would travel from the mouth of the Fraser River to Desolation Sound in about four days. This migration speed would take the peak of the smolt migration from Chilko Lake (May 3, average from 1998 to 2008) at 1285 m elevation to Queen Charlotte Sound (642 km downstream + 215 km by a great circle distance from Sandheads lightstation at the mouth of the Fraser River) in 19 days (May 22). Clearly this is too fast as limited contemporary sampling between mid-May and mid-June did not find Fraser River sockeye salmon postsmolts north of Queen Charlotte Sound[54], which also agrees with historical sampling[35] that sockeye salmon postsmolts are not reaching Queen Charlotte Sound until at least the end of June. It suggests a migration speed of about half that of the Redfish Lake sockeye salmon.

Updated estimates of Redfish Lake sockeye salmon migration speeds are 14 to 35 km d^{-1} and new information on migration speeds of coded-wire tagged Cultus Lake sockeye salmon that were recovered in 2008 and 2009 indicated an estimated migration speed of 14 to 19 km d^{-1}[1; 55]. At this speed, travelling in a straight line, the fish would travel from Sandheads to Redonda Island at the northern end of the Strait of Georgia in about 15 days. In Barkley Sound, however, the estimated average migration speed in tidal waters was only 1.6 km d^{-1} from May to July[56]. The reason(s) for such highly variable migration speeds among populations entering the ocean at different locations is unknown, but those with the farthest to travel to better sockeye salmon feeding areas (Alaska Current) may have evolved this strategy.

2.4 Factors Affecting Postsmolt Migration Behaviour

A numerical hydrodynamic model[57] forced by winds, Fraser River discharge, and tides indicated that surface currents in the Strait of Georgia, forced mainly by local winds, can affect the migration route used by Fraser River sockeye salmon postsmolts within the Strait of Georgia. Use of the western route by modelled sockeye salmon postsmolts increased only when strong, persistent northwesterly wind pattern became established in the Strait of Georgia. Model results with migration routes of north, northwest, and west at 4 cm s^{-1} produced residence times in the Strait of Georgia at 21 to 38 days. The best fit between the model and observations for 1984 (24 days in the Strait of Georgia) was obtained using a 4 cm s^{-1} swimming speed and a northwest orientation[53]. Furthermore, the tides and discharge in 1984 had no discernable effect on the migratory route followed by sockeye salmon postsmolts in the model.

2.5 Postsmolt Feeding

Following LeBrasseur[58], *stomach content* is used rather than *diet* because some unknown portion of the stomach contents may have been the prey of animals that the sockeye salmon ingested. Trophodynamic studies of fishes in the Strait of Georgia in the 1960s provided the first comprehensive data on sockeye salmon postsmolt diets. The earliest migrants into the Strait of Georgia had the least diverse diets (Table 2.5). Copepods were the dominant prey item in April. In all years, the percentage of copepods in diets diminished by month.

Copepods are an important trophic link between primary producers (phytoplankton) and higher trophic level carnivores in the Strait of Georgia[59]. The dominant copepod in the Strait of Georgia has been *Neocalanus plumchrus* but marked changes in species composition occurred in the 1970s with increases in *Calanus marshallae* and *C. pacificus*[60]. *N. plumchrus* has a peak abundance in spring until the late-stage copepodites descend to enter diapause until the following spring. In preparation for diapause, this copepod stores lipids to utilize from summer to winter and this characteristic makes it an energetically rich prey but its seasonal timing makes it available to sockeye salmon for only a relatively short period. El-Sabaawi[61] described an 87% decline in its abundance between 2001 and 2006. Because sockeye salmon tend to feed opportunistically, the full consequences of declining *N. plumchrus* abundance in the Strait of Georgia to sockeye salmon postsmolt growth and survival are unknown. As the field phase of this doctoral project ended in 2006, there were no equivalent zooplankton samples in 2007. During the years of *N. plumchrus* decline, the composition of the phytoplankton spring bloom varied annually among diatoms, diatoms and flagellates, and diatoms and dinoflagellates. The declines in *Neocalanus* were accompanied by longer term declines in copepod zooplankton biomass in the Strait of Georgia[62].

Table 2.5: Percentages of prey items in sockeye salmon postsmolt stomachs in the Strait of Georgia, by month, from 1966 to1968.

Taxon	4	5	6	7	Total
Amphipod	6.8	10.5	0.8	8.7	2.5
Barnacle	0.0	0.2	0.4	0.2	0.3
Cladocera	0.0	0.1	4.2	0.0	3.2
Copepod	90.9	45.0	8.0	6.8	20.7
Decapod	0.2	0.3	0.2	14.3	0.4
Eggs	0.0	3.1	63.7	1.4	49.7
Euphausiid	0.1	0.6	12.4	0.8	9.7
Fish	1.6	2.2	0.7	3.7	1.0
Insect	0.1	0.5	1.3	39.6	1.6
Larvacean	0.0	35.5	7.9	0.2	9.9
Mollusk	0.0	0.0	0.0	9.3	0.1
Ostracod	0.0	1.1	0.4	3.9	0.5
Polychaete	0.0	0.0	0.0	10.1	0.2
Sagitta	0.2	0.6	0.0	0.7	0.1
Worms	0.0	0.0	0.0	0.4	0.0

Trawling in the Strait of Georgia in July and September between 1997 and 2002 provided 24,206 salmon stomachs[50]. Interannual differences in major taxa in the diets of pink, chum, coho, and chinook salmon were low, but the contents of sockeye salmon stomachs were not reported. Average stomach volumes and sample sizes were reported for non-sockeye salmon, but as the standard deviations were not reported, it was not possible to understand if there were statistically significant differences in mean stomach volumes between years. A later study of coho salmon stomach content composition in July and September in the Strait of Georgia from 1997 to 2007[63] suggests that the dominant factor determining the composition of stomach contents of coho salmon was related to seasonal changes in relative prey abundance or prey selection. Cluster analysis, which groups years based on their stomach content similarities, showed that coho stomach contents had more similarity within month across years than within year across months (Figure 11). All of the July samples are in one large cluster and all of the September samples, except 2003, are in another. September 2003 had a substantially higher proportion of amphipods compared with all other years/months of sampling. Considering the coho salmon that entered the Strait of Georgia in 2007, the placements of 2007 within each cluster suggest that there was nothing unusual about the diet composition, although there were more empty stomachs in coho salmon in 2007 than in other years[63]. Extended periods with an empty stomach is a common feature of many families of piscivorous fishes[64] so it is not possible to attribute physiological status to these animals from these data.

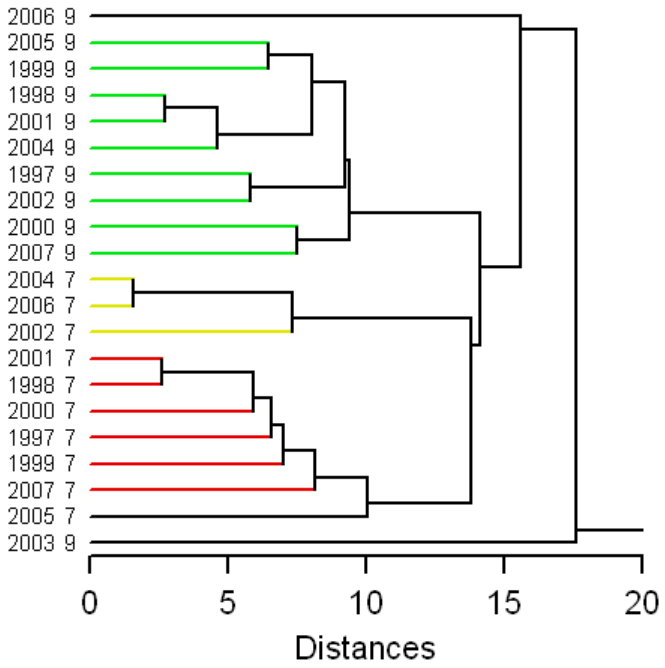

Figure 11: Hierarchical cluster analysis of relative composition of coho salmon stomach contents by year and month from 1997 to 2009. Identifiers indicate the year and month of sampling. Colours indicate cluster memberships. Data from Sweeting and Beamish[63].

Of the six sockeye salmon postsmolt stomachs examined from the mid-water trawl survey in Hecate Strait in November of 1963, three stomachs contained prey (*Limacina,* copepod, amphipod). These items were classified as undigested in two of the fishes. Whether these were Fraser River sockeye salmon is unknown but they are reported here because of the rarity of reports of autumnal samples in the coastal zone.

2.6 Postsmolt Growth

2.6.1 Strait of Georgia

The number of postsmolts, their average fork length, and the ranges of fork lengths of Fraser River sockeye salmon were summarized by year and month for the years 1966 to 1969[31]. Growth rates of Fraser River sockeye salmon postsmolts in the Strait of Georgia could not be determined from these data because the population of origin was unknown[31]. The pooled data from the Strait of Georgia only (excluding Saanich Inlet) reveal the dominance of postsmolts (age-1.x and age-2.x) until June, until underyearlings form the larger component in July in most years.

In the summer of 1968, repeated samples taken in Saanich Inlet, B.C. found that the abundance of sockeye salmon postsmolts increased rapidly from the end of May to a peak on June 7 after which their abundance declined rapidly (Figure 12). If the same population was sampled repeatedly, the growth rate was estimated to be 0.8 mm d^{-1}, or 4.25% of body weight, but the authors had no way of knowing if this was true.

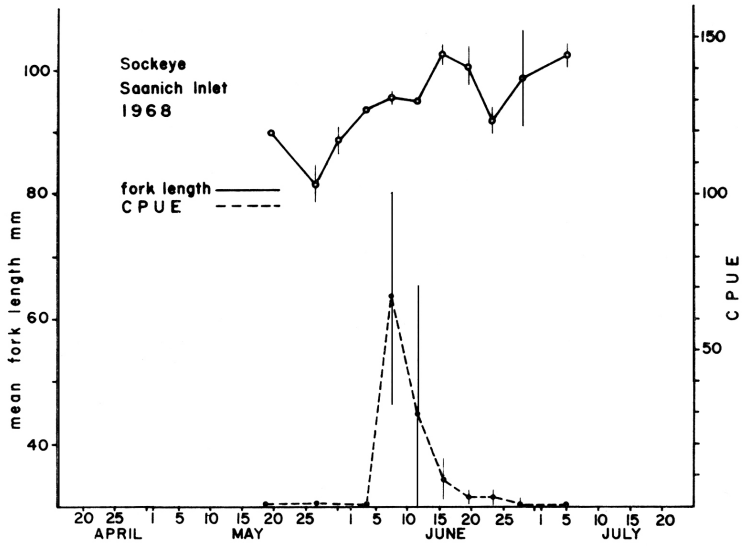

Figure 12: Size and abundance of sockeye salmon in repeated samples in Saanich Inlet, B.C. in 1968. Vertical lines indicate ±2 standard errors. Reproduced from Phillips and Barraclough[31].

In reviewing the studies conducted through the 1970s, Healey[36] found that the average size of sockeye salmon postsmolts caught in the Fraser River plume and in the Gulf Islands did not increase with time through the months April, May, and June. He surmised that the sockeye salmon postsmolts spent too little time in the Strait of Georgia to allow them to increase significantly in size. A major problem with determining growth rates of sockeye salmon postsmolts from repeated sampling in the Strait of Georgia is the high probability of a variable composition of the catch. Without knowing which populations were measured, a change in mean size over time could be a simple consequence of measuring a sample that contains a different population or mixture of populations at each sampling rather than from an effect of the growth of individuals. Increasing numbers of sockeye salmon fry migrating into the Strait of Georgia in summer will cause the mean size of sockeye salmon taken in samples to decrease because the fry are smaller (and younger).

Trawl surveys were conducted in the Strait of Georgia from 1997–2002[50]. Although the target sampling dates were July and September, problems associated with vessel scheduling did not permit the same locations to be sampled on the same dates each year. Nevertheless, it was possible to restrict the analysis of samples to two periods (July 1–15, and September 12–26) to provide more comparable results among years. Although not reported in the paper, it was possible to compute 95% confidence intervals on the mean lengths from the data reported (Table 3 in Beamish et al.[50]). For samples

collected in mid-September, at the end of the growing season, there were no significant differences among years in mean lengths of coho salmon, pink salmon, or chum salmon (Figure 13). There were significant differences among years for chinook salmon with smaller mean lengths in 1997 and 2002.

Mean lengths were more variable among years in samples collected between July 1–15 (Figure 14). The mean lengths of coho salmon sampled in July 2000, for example, were demonstrably larger than in other years, although its confidence interval overlaps that of the 1997 samples because of a small sample size in 1997. For chinook salmon, mean length was significantly different (smaller) from the other years only in 1998, otherwise there was no significant difference in mean length of chinook salmon among years. There was no significant difference in mean length of pink salmon in July among the three even years that were sampled. Mean lengths of chum salmon were significantly different among years in July, with 1997 and 2001 having the largest mean lengths.

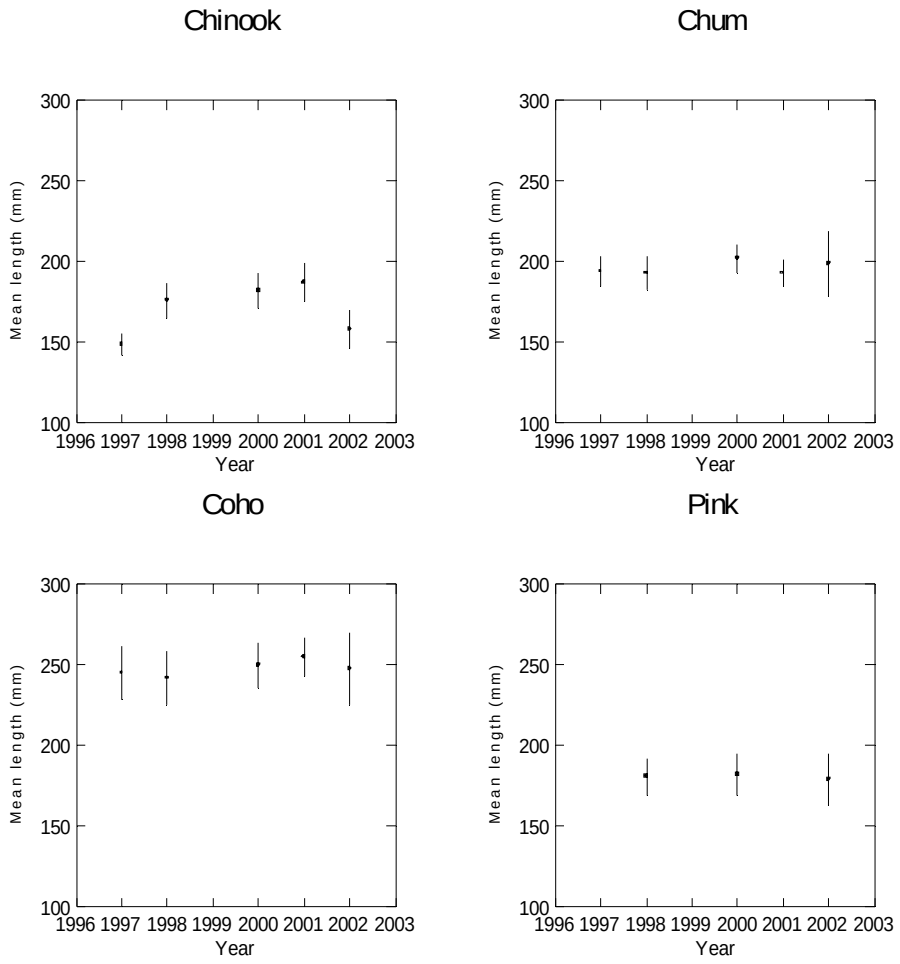

Figure 13: Mean lengths and 95% confidence intervals by year and species for Pacific salmon juveniles sampled in trawl nets between September 12–26, 1997–2002. Results computed from Table 3[50]. Samples in 1999 were not taken within these dates and were omitted.

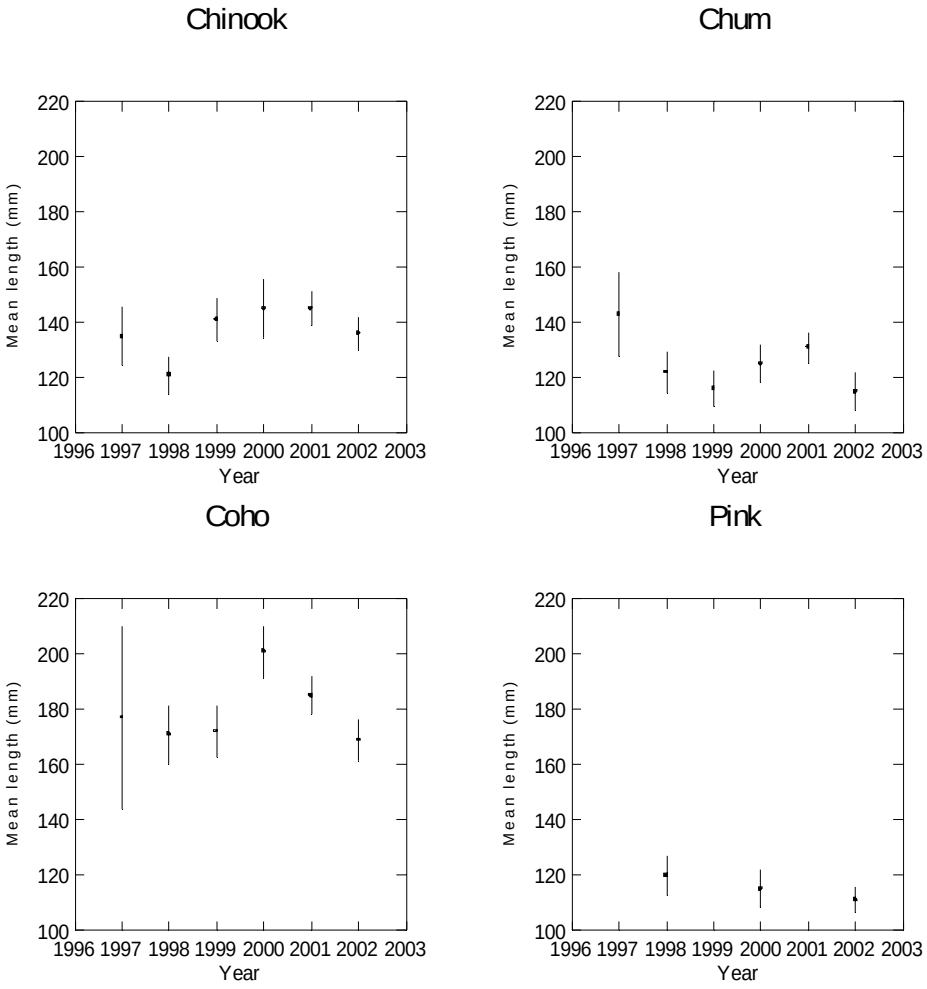

Figure 14: Mean lengths and 95% confidence intervals by year and species for Pacific salmon juveniles sampled in trawl nets between July 1–15, 1997–2002. Results computed from Table 3[50].

This comparison of mean lengths of non-sockeye salmon[ix] in the Strait of Georgia provides an indication of year to year variability in mean size of the juvenile salmon that were available to the trawl. These results were interpreted as evidence for improved juvenile Pacific salmon production in the Strait of Georgia after 1998 which was caused by changes in the speed of rotation in the Earth[50].

ix DFO reported to the Cohen Commission that it was unable to retrieve comparable data for sockeye salmon. (D.A. Levy, Cohen Commission, Sept. 10, 2010). As a result, an analysis of these data was not possible.

2.6.2 Continental shelf

Recoveries of maturing fish in southern B.C. fisheries that were tagged and released as postsmolts from 1965-1968 indicated that they had been larger postsmolts (18–22 cm, N = 12 tags) than similar recoveries in northern B.C. fisheries (14–19 cm, n = 14 tags)[35]. The larger size of southern B.C. sockeye salmon postsmolts was thought to be related to their earlier entry into saltwater and longer period of marine growth on the date of tagging. They also reported that the mean lengths of tagged postsmolts that survived two years to reach the fishery (0.8% of those tagged), tended to be larger than the overall mean length of all tagged postsmolts. They inferred that tagging mortality might be a cause of fewer smaller postsmolts surviving.

Contemporary surface trawl sampling provides a composite view of regional and seasonal growth and net energy accumulation by sockeye salmon postsmolts[10]. It was found that postsmolts sampled in northern locations had a larger mean size than those sampled in the south, and that energy density became progressively larger in northern than in southern samples from spring through fall. In general, larger postsmolts have greater energy density in each season (Figure 15). The noteworthy outlier appeared in Southeast Alaska in spring where the median body size was largest and median energy density was lowest. As seasons were selected from calendar dates in this analysis, what was classified as spring in most locations (May–June 20) may have been ecological winter or early spring in Southeast Alaska. In all other seasons, higher median energy densities were found in samples with larger postsmolts. In each season except spring, the larger postsmolts with higher energy densities were found along the Alaskan coast rather than along the B.C. coast. Note that energy was measured in joules g^{-1} to adjust for the effect of increasing mass on increasing energy, so the appearance of increasing energy density associated with increasing size suggests that larger size allows postsmolts to accumulate energy at a faster rate than for smaller postsmolts[10].

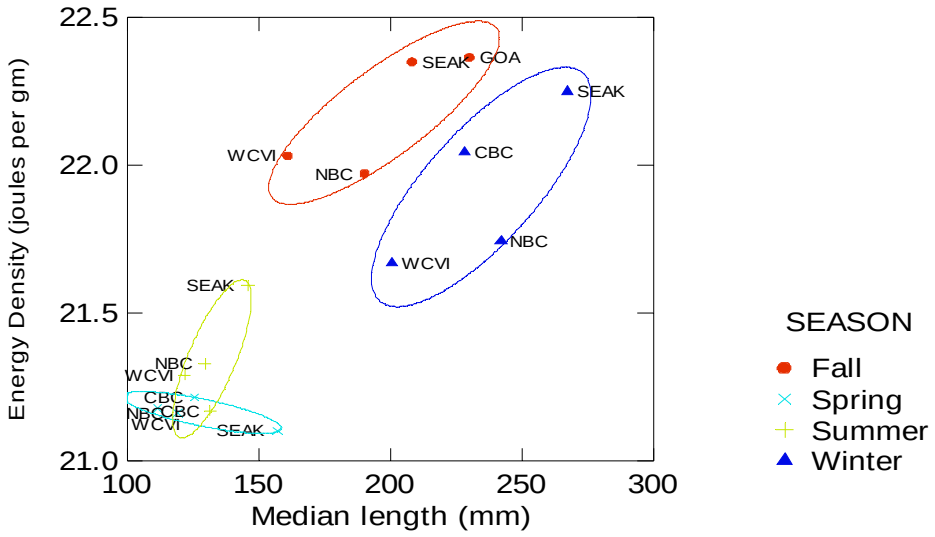

Figure 15: The median energy density (joules g^{-1}) of sockeye salmon postsmolts, by region and season. Ellipses indicated the 75% probabilities where the bivariate mean values in each season may be found. Data reproduced from Figures 8 and 9 in Tucker et al.[10].

The pattern of ellipses in Figure 15 reflects seasonal patterns in median length and energy content. The winter ellipse is somewhat lower and to the right of the fall ellipse, but the cause of the difference can only be a matter of speculation. The median length of a sample of postsmolts can be larger in winter than in the previous fall because the fish continue to increase in length, or because the median length becomes larger because the smaller individuals are dying faster rate than the larger ones. Although both processes may be at play in these data, it takes a rather substantial amount of mortality to change a mean/median length of a population by this process alone. Therefore, the different positions of the ellipses in Figure 15 likely reflect a winter feeding environment where less food is available. Some growth continues through the winter, but some energy reserves are used in metabolism.

Summary – Sockeye salmon emigrating from rivers in the southern part of their range have lower growth rates and lower average marine survival than their counterparts in Southeast Alaska[65, 10]. Therefore, it is not unreasonable to consider the initial period of their postsmolt migration as a "race" northward to find better feeding conditions in coastal Alaska. The idea of a race was motivated by the observation that the fastest observed migration speeds, measured from tagged individuals of known origin, were found in the southernmost populations. Others, like the age-0.x ecotypes from the Harrison River, have evolved a very different strategy of delaying migration to the continental shelf until autumn.

3 Beyond the Continental Margin

> *"The discovery is reported to have been taken as a result of the investigations of Professor David Starr Jordan and his assistants that the refuge of the salmon between the time of spawning in the Fraser and the return to the river fully matured is ten miles off the Vancouver Island."*
>
> The British Colonist, August 18, 1909

Professor Jordan was President of Stanford University and a leading ichthyologist of his generation. His ideas about salmon migration and distribution at sea[66], however, reflect how imagination (or bias) can entertain such fanciful stories when adequate data are not available to challenge them.

This section focuses on what is known about Fraser River sockeye salmon biology during the period after their postsmolt year and before the calendar year when they mature. For most Fraser River sockeye salmon, this is a twelve–month period of finding food, growing, and avoiding predation and disease in the Northeast Pacific. For some life-history types, typically those with slower growth rates, this can be a two-, or rarely, a three-year period.

3.1 Distribution and Migration

The distribution and movement of immature Fraser River sockeye salmon at sea is the least understood of all life history phases. Sockeye salmon that were tagged at sea were rarely recovered in fisheries the following calendar year, despite a significant effort directed at catching and releasing tagged salmon (Figure 16). In 1962, for example, four Canadian chartered salmon fishing vessels were deployed from April to July, each making about 7 trips of 10 to15 days each during spring and summer throughout the Gulf of Alaska north of 45°N and west to 160°W[67]. Each vessel was a ~24 m purse seiner that had been re-configured to catch salmon alive with baited floating longlines. Because it was not possible to determine, at the time of tagging, whether a fish was immature or maturing, it was not possible to know if the longline catches were representative of immature sockeye salmon populations. Only when the tag was recovered did the developmental state of the fish become known. The vast majority were maturing sockeye salmon.

Fishing gears tended to be selective for maturing sockeye salmon but the winter period, when the Gulf of Alaska is almost dominated by immature individuals, is poorly sampled. The first trans-Pacific winter survey for Pacific salmon was conducted by the Fisheries Agency of Japan only as recently as 1996[68]. The *Kaiyo Maru,* a large research stern trawler caught only 51 sockeye salmon from 22 stations in 1996 and half of these were taken in one set in the central Gulf of Alaska. Similar results with no catch were obtained from DFO surface trawl sampling the Gulf of Alaska in four years of sampling in the 1990s[69, 70].

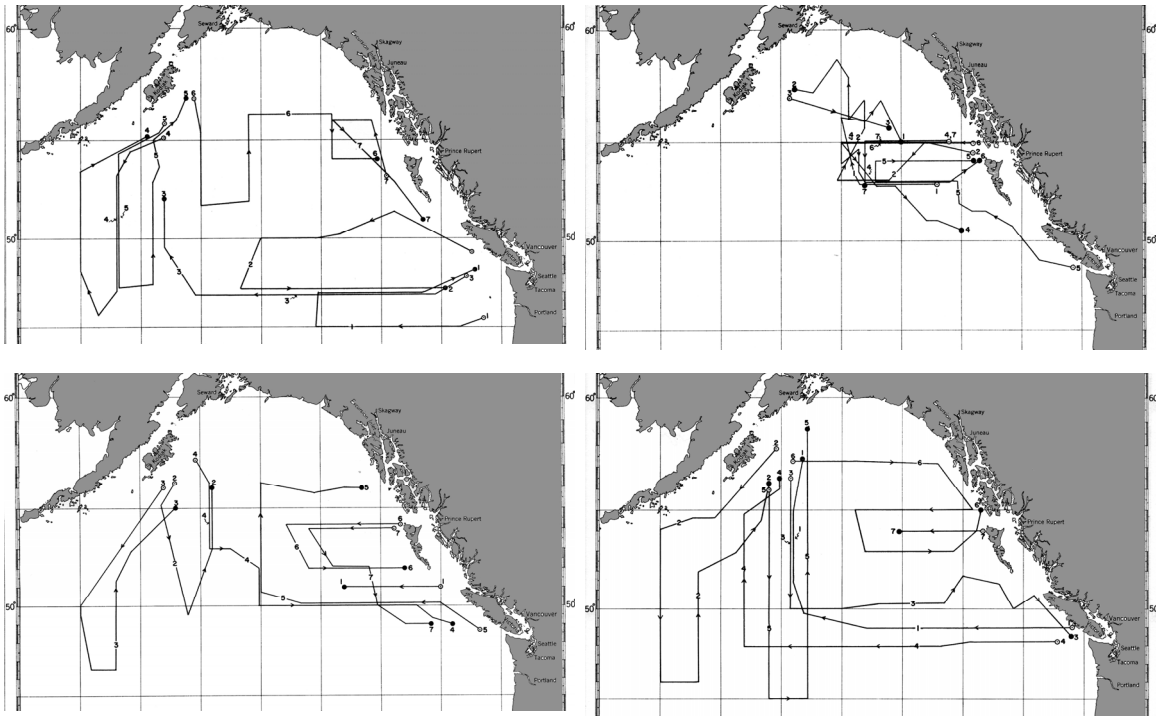

Figure 16: Cruise tracks of four vessels conducting Fisheries Research Board of Canada salmon research with floating longline gear in the Gulf of Alaska in the spring and summer of 1962.

The distribution of immature Fraser River sockeye salmon on the high seas, determined from very few tags, differs somewhat from that of maturing fish (Figure 17). Immature Fraser River sockeye salmon generally have a more southerly distribution[14] than maturing fish and two immature Fraser River sockeye salmon were tagged considerably farther west than any maturing fish. Some of the difference between the two groups is a result of bias introduced by tagging maturing sockeye salmon during their homeward migration when they are expected to be closer to the Fraser River compared to fish that are not on a spawning migration.

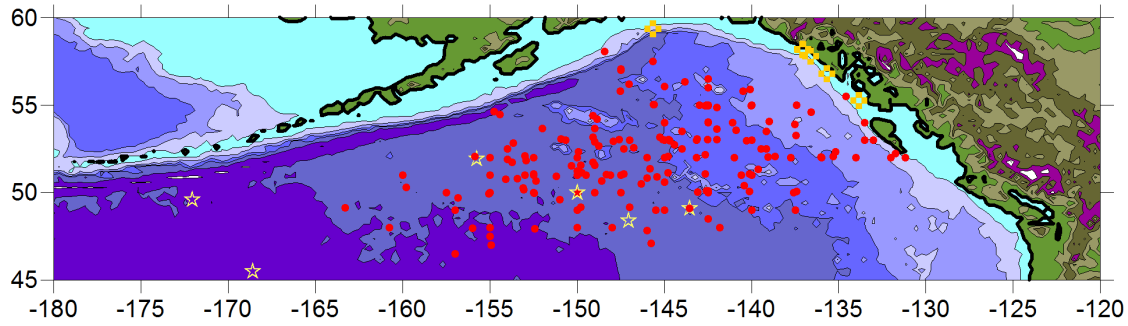

Figure 17: Locations of sockeye salmon caught on floating longline gear, tagged and released on the high seas and subsequently recovered in Fraser River salmon fisheries. Life history stages are indicated by different symbols; red dots = maturing fish, beige stars = immature, mustard crosses = postsmolts. Database currently maintained by North Pacific Anadromous Fish Commission, Vancouver, B.C.

The feeding migrations of immature sockeye salmon are not well known because there are few direct observations[71]. Winter observations are rare so the period between postsmolt and immature is one of the least well known. Models of migration that involve loops around the Gulf of Alaska are among the more common because they follow the geostrophic currents[72, 73] (Figure 18), but other models such as simple undirected swimming during the immature phase gave satisfactory results when compared to the available data[74].

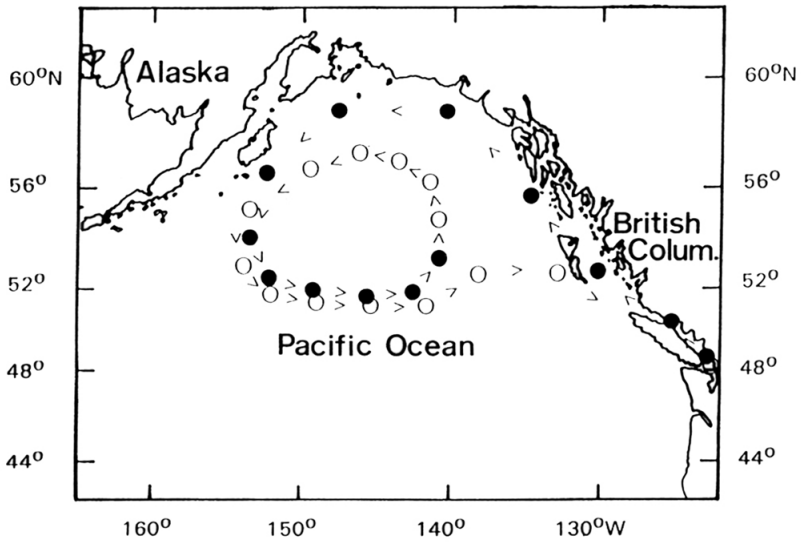

Figure 18: Hypothetical migration of early Stuart sockeye. Closed and open circles represent the first and second year of ocean residency, respectively. From Brett[72] in Hinch et al.[73].

The general migratory routes of immature sockeye salmon at sea were not determined from tagging data alone[14]. Catches were taken by other gears for other purposes and these contributed significantly to the general understanding of the routes. However, they suffered from a lack of stock-specificity. Sex and maturity were determined by visual inspection of the gonads. It is clear, however, from an examination of the length frequency data that immature sockeye salmon are under-represented in high seas catches, even when non-selective fishing gears (multi-mesh gillnets or seines) were used (Figure 19). On average, immature fish must be more abundant than maturing fish because the latter have experienced at least an additional year of mortality that the former have not, yet the younger/smaller fish are rarely found as the most abundant size-class in the catch. Even in 1957, when the immature phase of a very large return of late-run sockeye salmon to the Fraser River (in 1958) was at sea, the length frequency distribution resembled that of Figure 19. Either the gear favoured maturing salmon, or the immature salmon were elsewhere. As a consequence, it appears that some aspects of this life history stage are not as well known as for maturing fish.

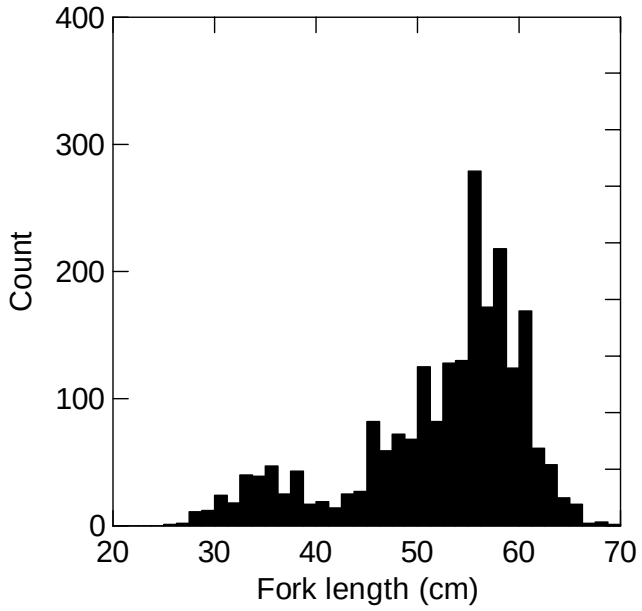

Figure 19: Fork length distribution obtained from sockeye salmon caught multi-mesh gillnet sets in the Gulf of Alaska from 1956–1958. Data from Neave and Manzer[75] and Manzer and Neave[76, 77].

French et al.[14] described how immature sockeye salmon were found in winter (February) in parts of the ocean with sea surface temperatures (SST) in the range 5.6–6.7°C, whereas maturing sockeye salmon were found where SSTs in February were 2.2–4.4°C. In more contemporary sampling by Japanese research vessels to 2002, Nagasawa and Azumaya[78] found that most age x.1 sockeye caught in the North Pacific in June were immature and were found where the long-term average sea surface temperatures were in the range 5–8°C. The Gulf of Alaska was not sampled well during these surveys in June and long-term average temperatures there were higher. In July, immature sockeye salmon were found mainly along the Aleutian archipelago (probably Alaskan sockeye) and in the Gulf of Alaska (mixture of origins) at SSTs <12°C. The Gulf of Alaska was not sampled in August in Japanese research vessel surveys from 1972. The extent to which these temperature and abundance patterns applies to Fraser River sockeye salmon cannot be determined from these data.

While the general model of the distribution of sockeye salmon places them mostly offshore in their first year as immatures (Figure 20), one cruise in late April to early May of 1998 (Figure 21) found small (20–30 cm) immature sockeye salmon aggregated within 6 nmi of shore in the southeastern Bering Sea[79]. This was the first such observation for the southeastern Bering Sea. The origins of these fish are unknown.

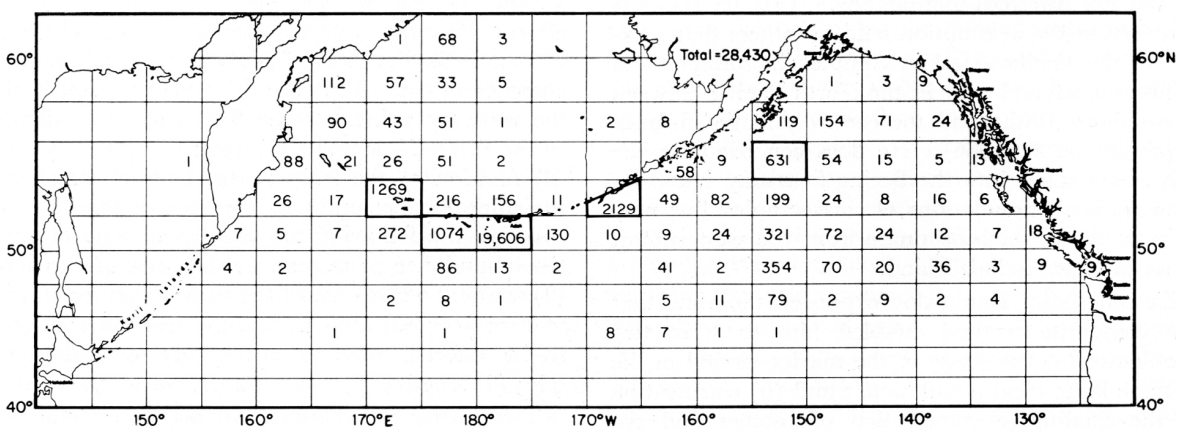

Figure 20: Distribution of tagged age x.1 sockeye salmon (nearly all immature) from 1956–1970. Areas with >500 fish tagged are outlined in bold. Figure reproduced from French et al.[14].

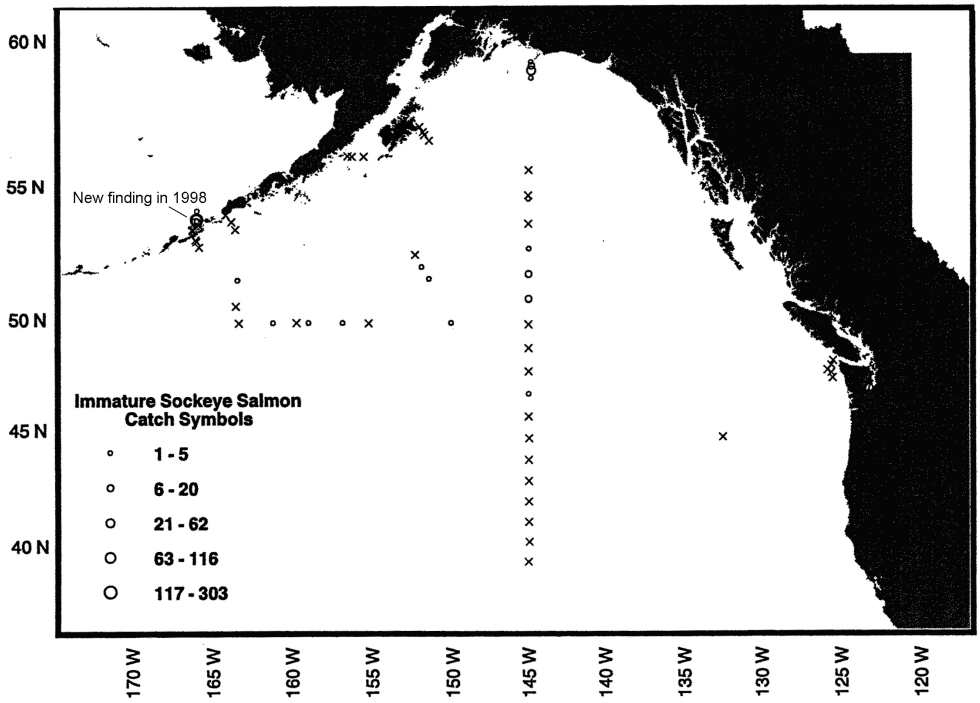

Figure 21: Distribution of fishing stations (x) and catches of immature sockeye salmon in the Gulf of Alaska in the spring of 1998. Figure from Carlson et al.[79].

Summary – From 1956 to 1970, 28,430 tags were applied to age x.1 sockeye salmon and a Pacific-wide total of 150 of these tags was recovered (0.5%). The distribution of immature Fraser River sockeye salmon at sea is poorly known because so few tags have been recovered from these fish. A combination of factors is probably responsible for poor recoveries of immature sockeye: tagging mortality, high seas fisheries during that era, and natural mortality before maturing. Certainly, some postsmolts are known to follow the continental shelf. If all of them have this behaviour, it would place greater numbers of immature salmon in the western Gulf of Alaska by the end of the postsmolt migration. Indeed the greatest number of tags applied to immature sockeye salmon of all origins in the Gulf of Alaska occurred south of Kodiak. As Alaskan sockeye salmon are known from this region, a significant fraction may have that origin. The fraction of westward migrating Fraser River sockeye salmon that leaves the shelf before reaching the western Gulf of Alaska is unknown. Neither gillnets nor longlines capture immature sockeye salmon in relation to their abundance. On average, it must be greater than the abundance of maturing fish because of the mortality that occurs in the year(s) between immaturity and maturity. However, most length frequency plots of sockeye salmon taken on the high seas feature a greater abundance of older fish (Figure 19), so it is not unreasonable to assume that certain aspects of the distribution of this life-history stage in the sea are known rather poorly.

3.2 Behaviour

Knowledge of the behaviour of immature sockeye salmon on the high seas has, for the most part, been obtained by catching salmon and inferring behaviour from the observed patterns in the catches. A potential explanation for the under-sampling of immature sockeye salmon in high seas catches (Figure 19) is that they behave differently from maturing individuals, and as a result, they are not equally vulnerable to the fishing gear. Gillnet and floating longline are passive devices that require fish movement past the gear (directed in the case of gillnet) or feeding behaviour. The floating longline may also be selective for certain sizes of fish because of hook and/or bait size[80]. The purse seine, on the other hand could potentially capture all size-classes if the immature and maturing fish occupy the same space.

Direct comparisons of the fishing characteristics of each gear at the same time and location in offshore waters are few. On May 26, 1964, a comparison of only longline and purse seine was conducted in INPFC area W5048 (between 48–50°N and 150–145°W). Immature sockeye salmon (~33 cm average) were fewer than larger individuals in both gears and the largest mode was represented in the longline but not the purse seine (Figure 22). Potentially, immature fish are routinely under-represented in the seine gear in this region but this cannot be determined from one day of fishing. That the purse seine did not catch fish in the largest mode was attributed to their having set the net in only 3 of 4 compass directions during the experiment[81]. The inference is that they would have caught the larger mode if the 4th compass direction was sampled.

> *"a difference in behavior of a particular component of the stock that affected its availability to the gear could cause a serious bias in the composition of the catch."*
>
> Hartt, 1975

The same logic, turned around, may indicate that bias in the catch composition suggests that different components of the stock behave differently. How differently has yet to be fully examined.

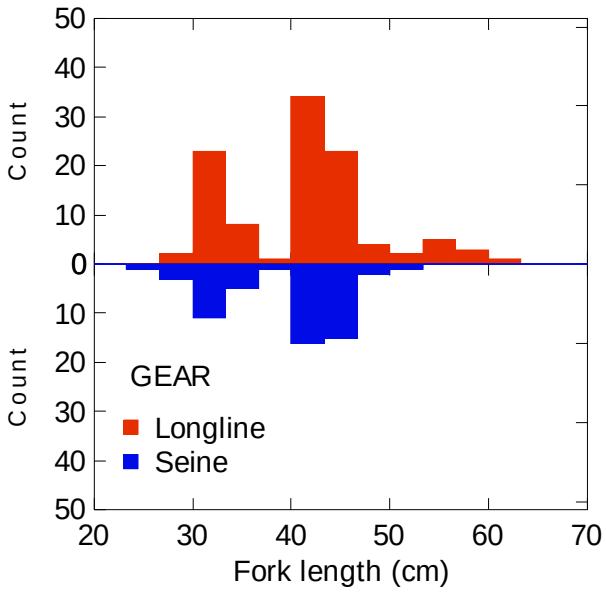

Figure 22: Fork lengths of 167 sockeye salmon caught offshore in the Gulf of Alaska on May 26, 1964 during an experiment to compare the characteristics of seine (3 sets combined) and longline gear (1 morning set of 20 skates). Data from Hartt[81].

Summary – The best evidence that immature sockeye salmon behave differently from maturing sockeye salmon it that they are not caught in adequate abundance in the gears typically deployed to catch them (purse seine, gillnet, longline). Multi-sized mesh gillnet and purse seine were thought to be non-selective. Immature salmon may lack the property of rapid and directed migrations that maturing salmon appear to exhibit. They have lower growth rates[82] than maturing fish and therefore less energetic requirements. Immature sockeye salmon potentially have no need to maintain a near-surface distribution for orientation during migration so they may not be exposed equally to the floating longline bait. The nature of the behaviour difference is mostly a matter of speculation.

3.3 Feeding

> *"Nothing is known of their feeding-grounds in salt water as they [sockeye] are never found in the bays and inlets which distinguish the coast and where the spring and coho are so common. It is thought that their feeding-ground must be in the open sea."*
>
> Anonymous, 1911

Salmon on the high seas forage opportunistically with stomach contents often related to oceanic domains and availability of certain prey types[83, 84]. The first samples of sockeye salmon stomach contents from the Gulf of Alaska were collected by the Fisheries Research Board of Canada during a gillnet survey in the summer of 1958[58]. Immature fish were identified by visual inspection of the gonads. The most noteworthy characteristic of the stomach contents of immature sockeye salmon was the small amount of material found in the stomachs. Amphipods, euphausiids and squid contributed the most. LeBrasseur[58] commented that there was a much greater difference in stomach contents among oceanographic domains than among species. Stomachs collected from salmon in the Alaskan Stream were dominated by fishes while those taken in the Subarctic Gyre were mostly squid.

A more complete analysis of the stomach content data that were collected from 1956 to 1964 (Table 3.3) considered the effects of SST, body weight, latitude, longitude, year, day of year, and time but they were able to describe only small amounts of variation in feeding probability (13%) and stomach fullness (16%)[85]. The lengths and weights of these fishes reflect the multiple age-classes and their seasonal changes in the samples (Figure 23, Figure 24). In this analysis, all individuals >500 g were pooled as "sub-adults" regardless of whether they would or would not mature in the upcoming summer, and there was no accounting for differences that might exist among stocks. LeBrasseur's[58] comments, above, suggest that immature and maturing sockeye salmon have different feeding behaviours. Despite these shortcomings in the analysis, in the pooled results Rand[85] found that the feeding and growth indices that he developed were variable in space and time in the Gulf of Alaska. There was a negative association between increasing SST and feeding probability (determined from presence/absence of contents in stomachs) but stomach fullness increased in warmer SST. Feeding probabilities of larger sockeye salmon were higher in winter and spring and lower in summer. The lower feeding probability in larger sockeye salmon was interpreted as evidence of anorexia prior to the spawning migration[85] but the timing of the onset of anorexia is not well documented. Rand[85] found that there was a tendency for larger sockeye salmon to be caught farther north than smaller sockeye salmon in the winters of 1963 and 1964 (combined). There was a tendency for larger sockeye salmon to be caught further north in the spring of 1962. He also found that in both the springs of 1962 and 1963 there was a sharp reduction in his growth index along the southern Gulf of Alaska.

Table 3.3: Total numbers of immature sockeye salmon stomachs examined by the Fisheries Research Board of Canada from 1956 to 1964 by year and month.

Month	1956	1957	1958	1959	1960	1962	1963	1964	Total
1	0	0	0	0	0	0	37	35	72
2	0	0	0	0	0	0	1	11	12
4	0	0	0	0	0	11	69	0	80
5	9	3	70	29	0	14	93	0	218
6	1	132	39	177	2	78	0	0	429
7	49	113	0	19	7	18	0	0	206
8	0	17	4	0	0	0	0	0	21
11	0	0	0	0	0	0	3	0	3
Total	59	265	113	225	9	121	203	46	1041

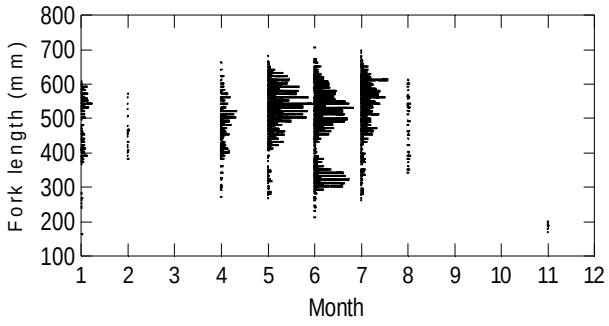

Figure 23: Fork lengths (mm) of sockeye salmon taken by multi-mesh gillnets and floating longline gear in the Gulf of Alaska from 1956 to1964 that were examined for stomach contents. Samples in November were collected by mid-water trawl net in Hecate Strait.

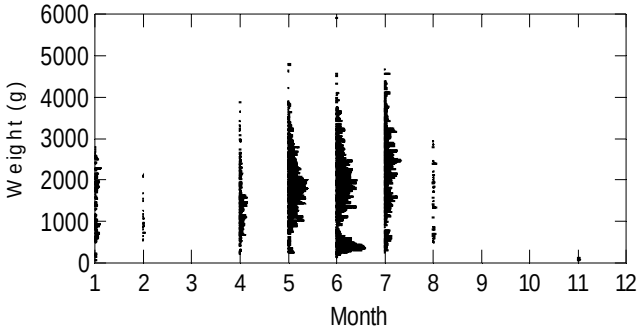

Figure 24: Body weight (g) of sockeye salmon taken by multi-mesh gillnets and floating longline gear in the Gulf of Alaska from 1956 to 1964 that were examined for stomach contents. Samples in November were collected by mid-water trawl net in Hecate Strait.

In 1981, a joint Hokkaido University–Oregon State University study of diel feeding patterns was conducted during a 24-h period from July 13–14 on board the T/V *Oshoro maru* in the Subarctic Gyre between latitudes 54° 51.5′ and 54° 57.9′N, and longitudes 144° 55.1′ and 145° 11.3′W[86]. Two gill nets, each 800 m long and 6 m deep, with 300 m of115-mm, 250 m of 121-mm, and 250 m of 130-mm (stretch) mesh, were alternately fished throughout the period. The total catch of sockeye salmon was the largest in night sets, as was the fraction of the catch taken in the uppermost part of the net. Prey composition for sockeye salmon had a diel pattern with euphausiids (predominantly *Euphausia pacifica* and *Thysanoessa longipes*) dominating at night[86]. Other common prey of sockeye salmon during this study were amphipods and fishes. Squids were more common in the afternoon/evening. Copepods formed <1% of the diet.

Kaeriyama et al.[84] conducted an evaluation of salmon diets from 1994 to 2000 but did not distinguish between immature and maturing individuals. The stomach contents of sockeye, pink and chum salmon tended to be zooplankton during this period while the other species of salmon fed on squid and fishes.

Summary – Samples of stomach contents of sockeye salmon in the Gulf of Alaska were collected from 1956 to 1964. The results of a single year of sampling (1958) was published in 1966[58]. As there was a large return of Adams River fish in that year, it might be reasonable to assume that some of these fish were of Fraser River origin. Data from samples collected in the Gulf of Alaska in 1962 and 1963 were reported in 2002[85], but this study did not distinguish between immature and maturing salmon although it did consider the effect of size (fork length) which can be a correlate of maturity at some sizes. Lebrasseur[58] drew attention to how little material was found in the stomachs of immature sockeye salmon compared to maturing fish.

3.4 Growth

Stage-specific growth of individual immature Fraser River sockeye salmon can be measured from the amount of growth that occurred between the first and second marine annulus on fish scales[87], but this measurement was not made routinely, except during a brief period in the 1960s by the Stock Assessment Authority of the Fisheries Research Board of Canada. The growth of immature sockeye salmon can be measured on individual fish that were tagged as postsmolts and recovered at sea the following year (or more for fish older than age 1.2). Generally, fork length measurements will have been made on the latter, but they are so few that a representative estimate of the growth of immature sockeye salmon will not be possible. Furthermore, the stock of origin of these tagged fish will not be known.

3.4.1 Density-dependent growth (intra-specific)

Intra-specific density-dependent growth of Fraser River sockeye salmon during their immature year in the Gulf of Alaska has not been studied. However, it is known from other B.C. sockeye populations that the largest correlations in mean fork length among different stocks, are found in fish maturing in the same year. The mean size of sockeye salmon from the same generation that share a common ocean-entry year, but different return years, are uncorrelated [88, 89]. Examining immature Fraser River sockeye salmon for the property of density-dependent growth, in relation to salmon abundance (various species), will require annual measurements of mean growth from scales but this is not done routinely. One study examined annual growth variation in the Early Stuart stock (Figure 25) and found that variations in the amount of growth in any year by a given fish is uncorrelated with the amount of growth observed at other ages for the same fish[90]. The implication is that there is no persistence of faster or slower growth within individuals of a given stock. It was also found that the factors affecting growth in different years were correlated suggesting that the oceanic factors affecting growth are stochastic rather than autocorrelated on an annual basis.[90].

Long-term trends in growth of the Early Stuart stock were largely confined to postsmolts or maturing sockeye salmon[90]. This was interpreted to mean that the coastal zone is food limited, i.e. the increased salmon abundance that was observed at the time may have resulted in increased trophic competition in coastal waters. Long-term trends in growth were largely absent among immature stages in offshore regions for M2 in age 1.2 and 2.2. individuals, and M2 and M3 growth for age 1.3 individuals (see Figure 25 for definitions of M1 to M4).

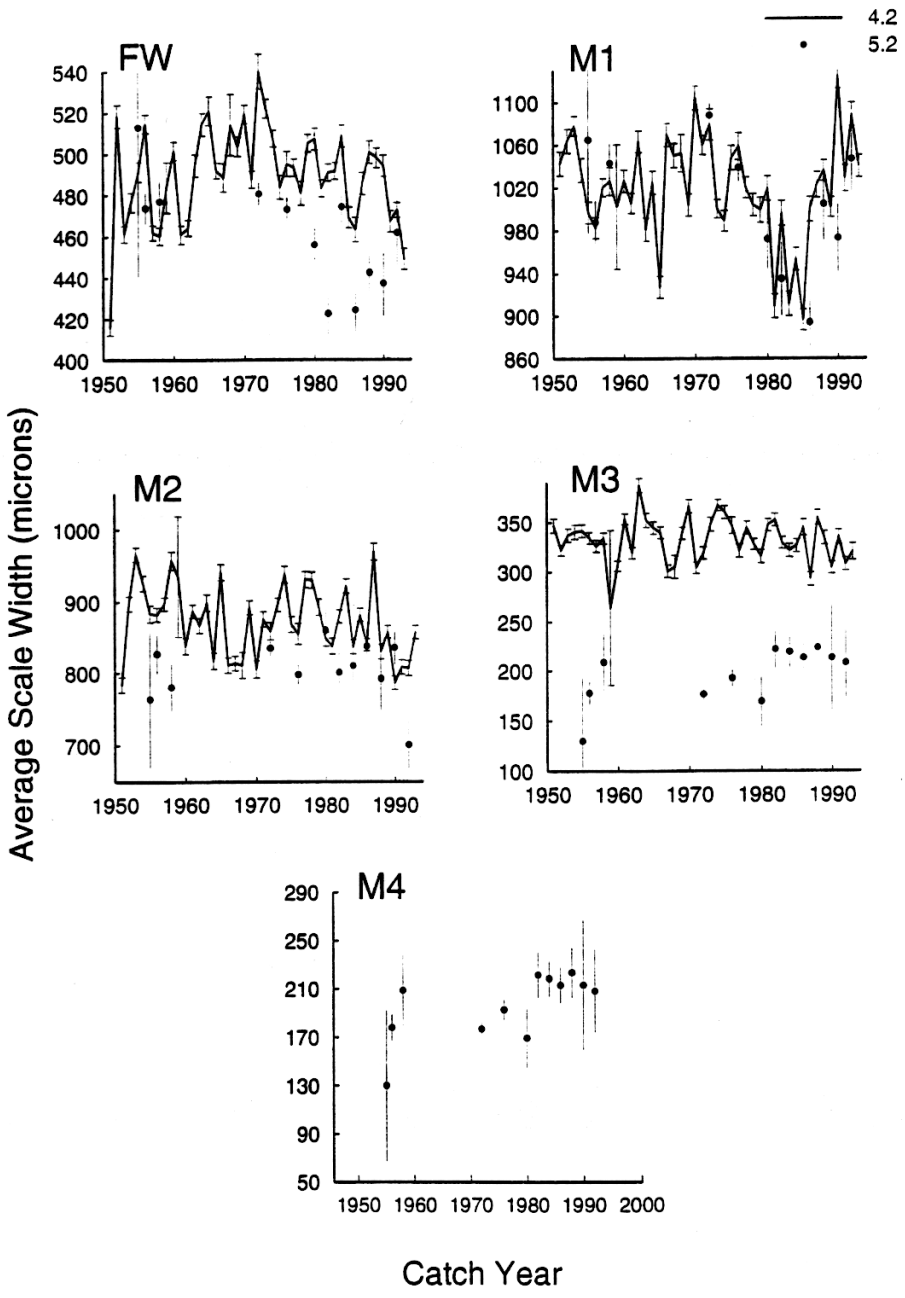

Figure 25: Stage-specific variation in marine growth by year for the Early Stuart stock of Fraser River sockeye salmon. M1 to M4 indicates the years at sea. FW = freshwater, M1 = postsmolt, M2 = immature (mature for jacks), M3 = maturing year (age 1.2) or immature year (age 1.3) and M4 = maturing year (age 1.4). The pattern of variation at different ages is uncorrelated. Dots indicate fish that matured as age 1.3 and solid lines indicate fish that matured at age 1.2. Figure from Welch[90].

Summary – Generally, the increase in fork length or mass of immature sockeye salmon is less than that of maturing sockeye salmon[82] because the immature fish do not have the joint energetic demands of a spawning migration and maturation. Maturing fish of the same length as immature fish tend to weigh more. Some measurements of annual growth of Fraser River sockeye salmon, determined from scale growth, exist but they are relatively rare.

3.5 Thermal Limits to Oceanic Distribution

In the 1990s, when the spectre of global warming began to feature more prominently in scientific discussion, a *thermal limit* hypothesis for Pacific salmon distribution attracted some attention[91]. The hypothesis followed from a report that the southern limit of Pacific salmon in the North Pacific Ocean is determined by the temperature of the surface waters. It argued that there are abrupt thermal limits to their horizontal distribution. The thermal limits in spring in the northeastern North Pacific were 8.9°C for sockeye salmon, 9.4°C for coho salmon, and 10.4°C for pink and chum salmon, although "spring" was not defined. This conclusion was followed by a more speculative paper[92] showing how increasing concentrations of greenhouse gases in the atmosphere would lead to global warming which would raise near-surface ocean temperatures in the North Pacific, restricting the spatial distribution of Pacific salmon in July to a region of the northern Bering Sea, about 1300 km more northerly than latitudes they currently occupy (Figure 26). The following material examines the thermal limit hypothesis using Intergovernmental Panel on Climate Change 4th Assessment Report (IPCC AR4) projections of SST in the North Pacific and salmon distribution data that were not available when the hypothesis was developed.

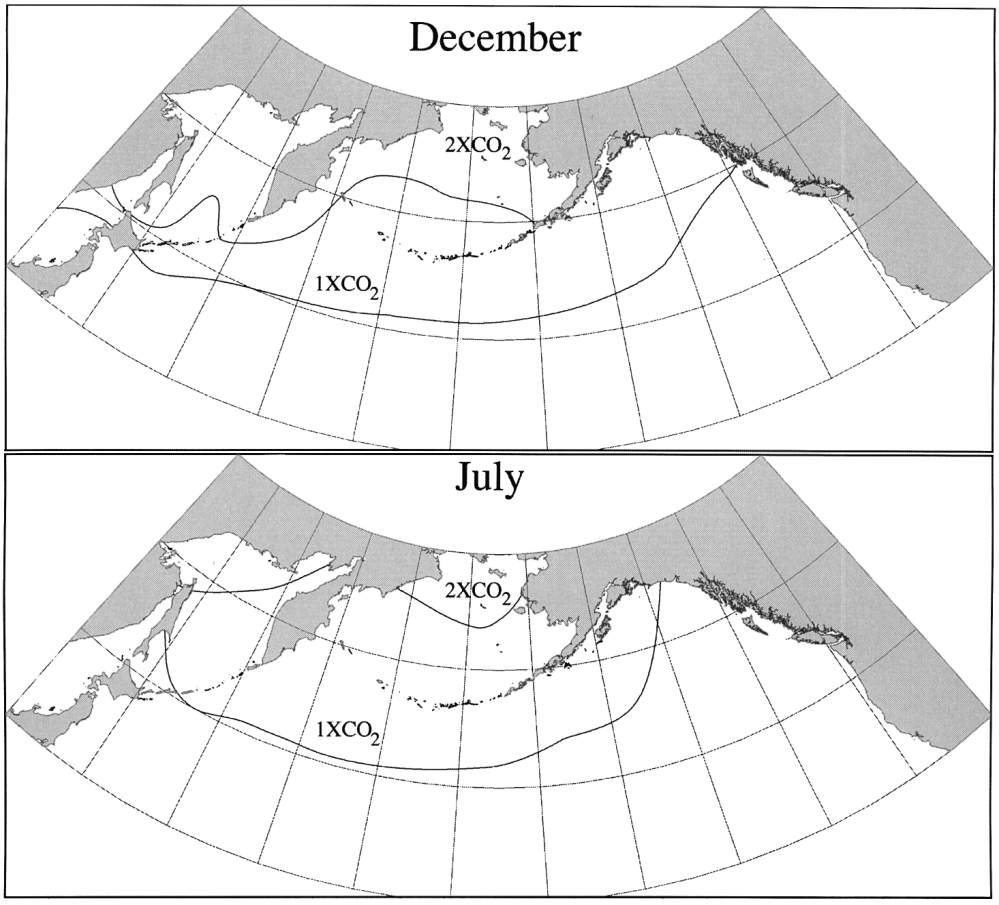

Figure 26: Comparison of the predicted winter (7°C) and summer (12°C) positions of the sockeye salmon distribution under current and future climates. With a doubling of atmospheric CO_2 the area of acceptable thermal habitat in the North Pacific is predicted to decrease to zero in summer and decline sharply in winter. Figure from Welch et al.[92].

3.5.1 Sockeye salmon in waters exceeding thermal limits

A survey to test the thermal limit hypothesis was conducted in March–April of 1995[93]. The 10.2°C isotherm was the hypothetical upper limit to salmon distribution. During the survey, 22 sockeye salmon were caught in two of a total of 44 tows that were distributed around the eastern Gulf of Alaska. No salmon of any species were caught at 75% of the stations. The survey was repeated in October–November of 1995 with the essentially same result: no salmon were caught in the Gulf of Alaska beyond 250 km from shore[69] although many (3,582) were caught on the shelf and 97% of these at bottom depths <200 m. After four years of catching no salmon in the deeper waters of the Gulf of Alaska, these offshore surveys were discontinued around 1998[70]. A number of explanations, some more plausible than others, come to mind for the lack of salmon: (1) the surveys were not conducted at locations where Pacific salmon occur, (2) the salmon were at depth beyond the reach of the surface trawl, or (3) the abundance of salmon was too low to be taken in the sampling conducted.

Welch et al.[92] established the 12°C isotherm in July as a thermal limit to Pacific salmon distribution. The movement of this isotherm northward with global warming was hypothesized to restrict their distribution northward, eventually into the northern Bering Sea (Figure 26). The ten warmest years (area-weighted average of gridded data within the bounds <160°W, >50°N) in July in the Gulf of Alaska were, in descending order: 1997, 2005, 2004, 1888, 1936, 1958, 1957, 1941, 1885, 1993). In some of these years, the T/V *Oshoro Maru* made regular cruises to the Northeast Pacific. Until 2002, scientific activities in the region included the deployment of surface gillnets of varying mesh sizes during the night. The warmest years when the *Oshoro Maru* was operating in the Gulf of Alaska were 1997, 1993, and 1983 but the ship cruise tracks in the Gulf of Alaska differed significantly among years. The only cruise with a North–South transect that spanned the hypothetical limit of 12°C was in 1997 (the warmest year). Sockeye catches in July 1997 were more abundant at temperatures greater than the thermal limit (Figure 27).

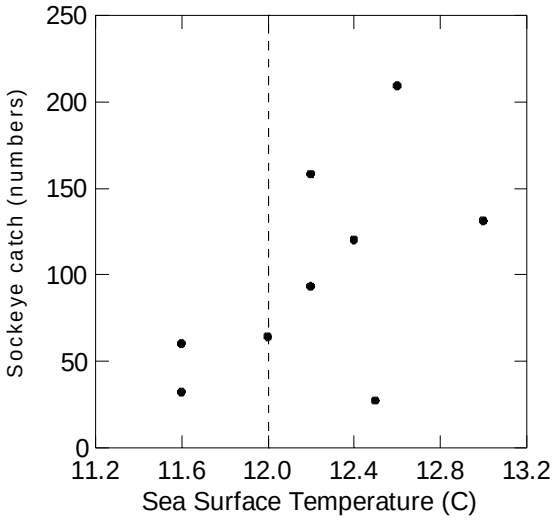

Figure 27: Numbers of sockeye caught in nightly gillnet sets by the T/V *Oshoro Maru* at different stations along 145°W during July 3–12, 1997 versus SST measured at the stations. Vertical dashed line indicates the temperature of the Welch et al.[92] thermal limit in July beyond which sockeye salmon should not be found.

During the latter half of the 1950s and in the 1960s, the Fisheries Research Board of Canada's North Pacific Survey conducted high seas fishing with gillnets and longlines throughout the Gulf of Alaska. Primary fishing stations were 50°N 155°W, 55°N 155°W, 50°N 145°W, 55°N 145°W, 58°N 145°W, 50°N 135°W, and 55°N 135°W. In 1957, for example, they caught a total 997 sockeye salmon of unknown origin in 71 nights of fishing. As the period of fishing extended from May until August of that year, it is possible to examine the relationship between the hypothesized thermal limit and sockeye salmon catches in the Gulf of Alaska. A two-sample Kolmogorov-Smirnoff test can be used to identify differences between catches above and below the hypothesized thermal limit. It indicated that there was no significant difference ($P > 0.97$) in the frequencies of sockeye salmon catches above and below the hypothesized thermal limit (Figure 28).

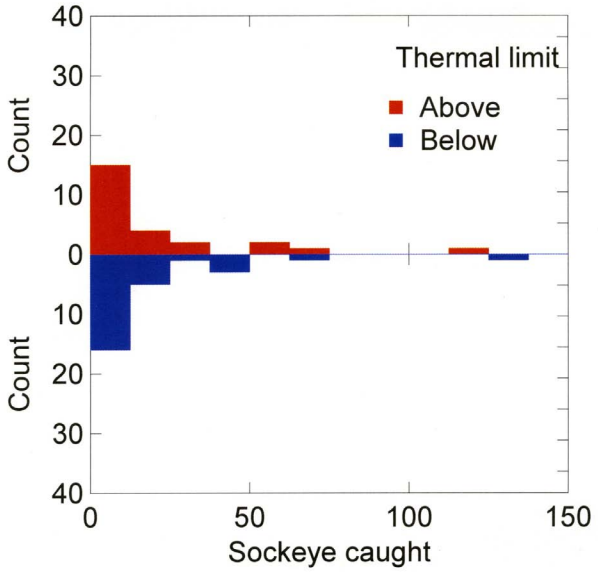

Figure 28: Sockeye salmon caught above and below 12°C during exploratory fishing for salmon throughout the Gulf of Alaska, May to August 1957.

If the 12°C SST isotherm represents a physiological barrier to sockeye salmon distribution, they could not have reached the eastern Gulf of Alaska and its major southern sockeye salmon rivers (Skeena, Fraser, Columbia) in most years. From 1982 to 2009, surface waters >12°C in July occupy much, and in some years, all of the eastern Gulf of Alaska. In warmer years like 1997, 2004, and 2005, the northward (and westward) intrusion of the 12°C isotherm along the coast can extend past Kodiak Island (Figure 29). In cold years, the 12°C isotherm extends in July only as far north as Haida Gwaii. Why 12°C should form a southern limit but not an eastern or northern limit is not explained by the hypothesis.

An alternative thermal response behaviour, where salmon might restrict their vertical migration to a few metres lower in the water column where water temperatures cool rapidly, was considered by the authors to be a novel behaviour that would not likely be adopted, even though this behaviour is used routinely by sockeye salmon fry in lakes[94, 95, 96]. Rand[85] argued that the reduced abundance of sockeye salmon along the southern periphery of the Gulf of Alaska was equally likely to be explained by a sharp reduction in growth potential rather than a behavioural response to SST proposed by Welch et al.[91]. He described a sharp decline in both feeding and growth of sockeye salmon in 1962 and 1963 in a region south of 52°N. The part of the Gulf of Alaska from 55°N to 58°N was most favourable for sockeye salmon growth in these years. The growth potential dropped by one order of magnitude with a change in SST from 6 to 7°C.

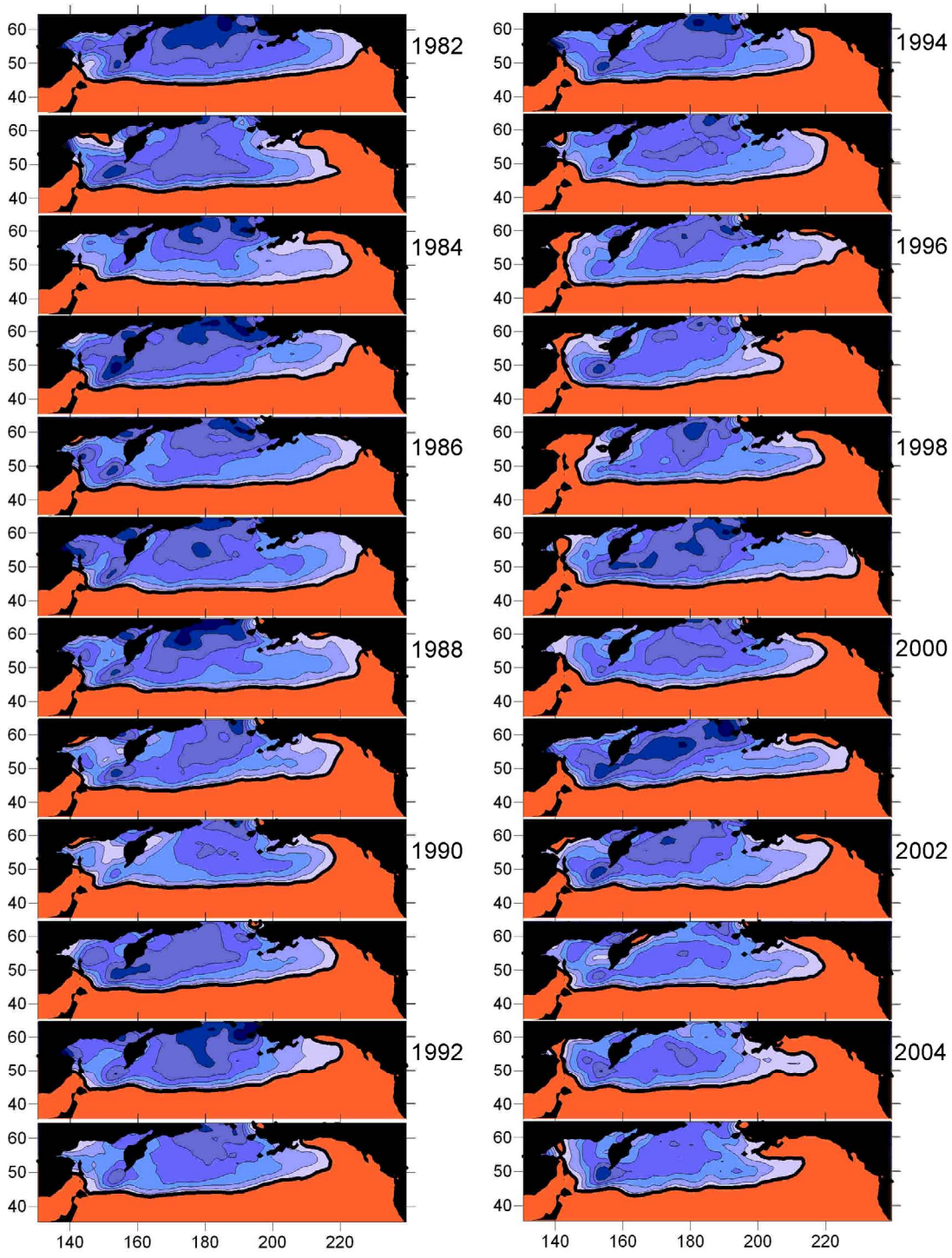

Figure 29: Sea surface temperature contours for the month of July from 1982 to 2004. The thick contour indicates the 12°C isotherm and all regions warmer than that are coloured in orange. Data are from the U.S. NOAA OIv2SST monthly gridded data.

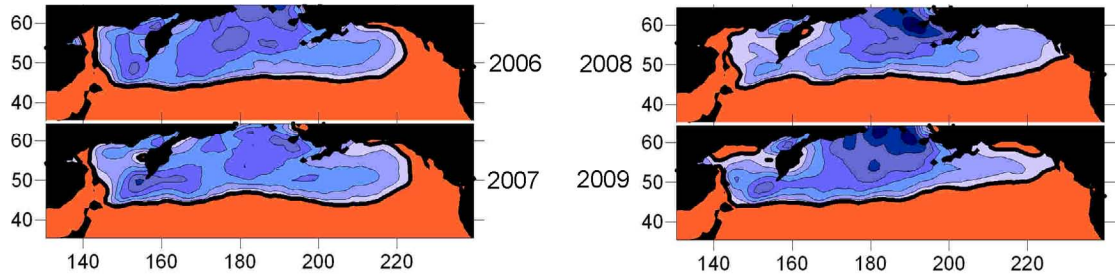

Figure 29: Continued, 2006 to 2009.

3.5.2 Global climate model projections

IPCC AR4 model expectations for the future state of average July SST in the North Pacific are different from what was published over a decade ago, and was used to consider the future state of sockeye salmon distribution (Figure 26). The IPCC A2 scenario (Figure 30) anticipated a doubling of atmospheric CO_2, from late 20th century concentrations, by the mid-2080s. Four models (hadcm3, cccmat47, gfdl2.1, and mirocM) were selected to examine because they have a better representation of North Pacific SST variability[97]. For each model, the 10-year average July SST in the 2080s was computed from the average of 10 years of SSTs during the 2080s. Smoothing of the average SSTs was done by the kriging algorithm in the contouring package SURFER™.

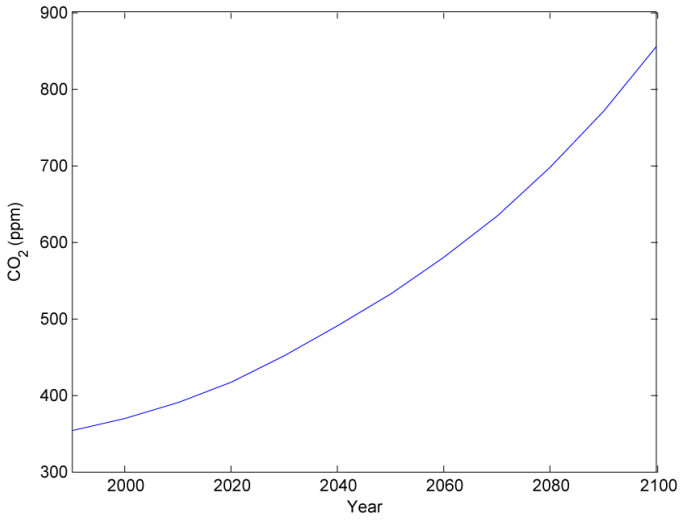

Figure 30: Projections of atmospheric CO_2 concentrations under the A2 scenario (business as usual scenario).

With the exception of mirocM, these models suggest that, on average, SSTs <12°C will not be a significant part of the Gulf of Alaska at twice the late 20th century CO_2 concentrations (Figure 31). However, none of these models yields a northward shift of the 12°C SST isotherm as extreme as was

reported by Welch et al.[92]; see Figure 26. Each of these IPCC models has a region of the North Pacific, south of the Aleutian archipelago, with waters <12°C. It is worth remembering that these models are computed on a relatively coarse grid compared to the small to mesoscale physical processes that can affect SSTs, especially on the continental shelves where these models are not expected to perform well.

What are currently considered July SST extremes at the beginning of the 21st century will become approximately the average state of nature with a doubling of CO_2 concentrations, according to these four models. The Julys of 1997 and 2005 (Figure 29) were relatively extreme years of widespread strong, positive SST anomalies and they bear a qualitative resemblance to the projected average SSTs in the late 21st century, under scenario A2. Both of these years coincided with relatively strong biological anomalies in Fraser River sockeye salmon. The most noteworthy were later than average run timing in both years[98, 99], although much more extreme in 2005, and high in-river mortality in 1997[98]. The total return of 7.1 million sockeye salmon to the Fraser River in 2005 was slightly higher than forecast but that total was a result of much lower than expected abundance of the Summer run and a much higher than expected abundance of the Late run[99]. Peak run timing to Area 20 (western end of Juan de Fuca Strait) in 2005 exceeded previous extremes by six days (Early Stuart), seven days (Summer). The average timing for Early Summers was exceeded by 29 days. The greater issue for the Fraser River sockeye salmon return in 1997 was the high in-river mortality and migratory anomalies[100]. However, both of these years of extreme SST had significantly greater returns than have occurred generally in the early 21st century.

Summary – The thermal limit hypothesis[91] anticipates that SST, rather than other oceanographic properties, regulates the range of Pacific salmon in the North Pacific Ocean. It proposes that global warming will move the 12°C isotherm in July to the northern part of the Bering Sea and this will restrict the geographic range of sockeye salmon in the North Pacific Ocean to a region around Bering Strait by the year when atmospheric CO_2 concentration reaches double that observed in the late 20th century[92]. The hypothesis is controversial because it considers that horizontal movement in space is the only option available to the salmon to avoid warmer surface temperatures. Achieving a cooler temperature by vertical movement requires only a few metres of movement whereas achieving the same degree of temperature change requires a horizontal shift of hundreds of kilometres. Sockeye salmon are known to make vertical movements in the ocean[86] and in lakes as juveniles to avoid warm surface temperatures.

The Intergovernmental Panel on Climate Change 4th Assessment Report included an analysis of many numerical dynamical models to understand the future of Earth's climate in the 21st century[101]. Several of the models that are known to have a better representation of the North Pacific Ocean revealed that the location of the 12°C isotherm in July under a doubling of CO_2 (by the 2180s under A2 scenario) is significantly farther south than was anticipated in the climate model used by Welch et al.[92]. The modelled future state of the surface ocean in the 2180s bears a qualitative resemblance to contemporary years that were considered relatively extreme (e.g. 1957, 1983, 1997, 2005). In some of these years, salmon research was ongoing in July in the Gulf of Alaska so it is possible to examine their distribution relative to the thermal limit. For the years when comparisons are possible, salmon were equally abundant above and below the proposed thermal limit. Nevertheless, very warm years tend to affect some aspects of Fraser River sockeye salmon biology, such as the extremely late return timing in 2005[102, 103].

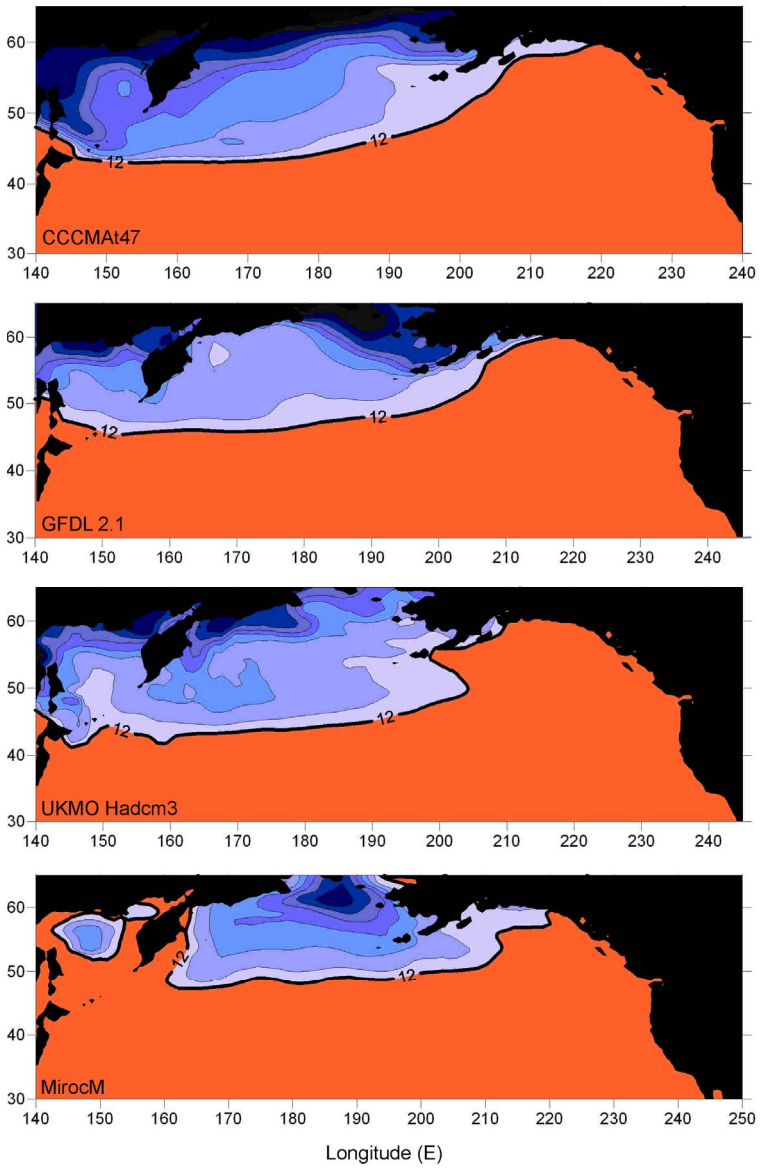

Figure 31: Average location of the 12°C surface isotherm in the North Pacific Ocean in the 2080s based on output from four IPCC models (named in lower left of each panel). Orange coloured regions exceed 12°C and counter intervals less than 12°C are spaced at 1°C.

4 Maturation and Migration

4.1 Distribution of Maturing Fraser River Sockeye Salmon

A detailed analysis of the age composition of approximately 32,000 maturing sockeye salmon caught by the Japanese mothership gillnet fishery in 1961 and 1962 in the northwestern Pacific Ocean and Bering Sea led to the conclusion that homogeneous populations of sockeye salmon (based on age composition) were found within 1° × 1–1.5° lat./long. blocks[104]. At a larger scale (2° × 5° lat./long.) age composition of the catches became heterogenous. This assessment was based on samples of catches that represented 35 and 38% of the total North Pacific sockeye salmon catch in these two years. An important result of this study, with regard to what can be inferred from typical research vessel catches that deploy small amount of fishing gear at predetermined stations in the ocean, is that they are not likely to be representative of the population of maturing sockeye salmon in the region where they were taken[104]. This potentially limits what can be inferred from high seas research sampling.

Nevertheless, most of what is known about stock-specific distributions of maturing sockeye salmon has been obtained from high seas tagging data[68], although other methods involving the identification of parasites with known distributions in freshwater[105, 106], or the characteristics of scale patterns developed in freshwater[107] have also been used with varying degrees of success. Tagging was preferred, as the stock identification tended to be less ambiguous than the other methods. The distribution of stocks in the North Pacific was a particularly important area of investigation for the INPFC, as distribution affected vulnerability to high seas salmon fishing. Less attention was paid during these studies to population-specific patterns of distribution, as the members of the Commission paid greater attention to the "continent of origin" or "national" distribution of stocks on the high seas.

From 1956 to the mid-1990s, the total number of sockeye salmon tagged at sea and recovered in British Columbia and reported to the INPFC or the NPAFC was 1,241[68].[x] Only four additional tags have been recovered in B.C. since that report was written so Myers et al.[68] reflect what is known at present. Tags recovered in general areas that are associated with Fraser River sockeye salmon fisheries were a result of two approaches: (1) seine sampling on the continental shelf of the Gulf of Alaska (404 recoveries) especially along the west coast of Vancouver Island, and
(2) floating longline sampling throughout the Gulf of Alaska basin (426 recoveries), mainly from 1962 to 1967.

Seining along the west coast of Vancouver Island in summer will tend to direct the tagging efforts toward maturing fish making their homeward migration. Considering only those recoveries of tagged fish that were taken in Fraser River recovery areas but were tagged offshore, where both maturing and immature sockeye salmon are expected to occur, there is a noteworthy imbalance in the ratio of mature:immature tags recovered (781 ÷ 10 = 78.1). Ten tags is the total number of recoveries of immature fish that were tagged the year before maturing and 781 is the number of recoveries of fish that matured in the same year as they were tagged. On average, this ratio must be <1.0 because cohorts are always more abundant when they are younger (immature) than when they are older

x The results of regional tagging studies associated with the activities of the Pacific Salmon Commission (e.g. North Coast tagging in the 1980s) tend not to be reported to the INPFC/NPAFC.

(mature) because of an additional year of mortality. If Ricker's 1976 estimate of monthly natural mortality during the last year at sea (0.015 m^{-1}) is used to approximate the abundance of a maturing cohort one year before maturity, it will be about 20% larger. In nature, therefore, the ratio of mature:immature should be about 0.83 if Ricker's estimates are reasonable. Applying these estimates to the number of mature fish recovered (781) suggests that ~940 immature sockeye salmon from British Columbia should be in the records. Where are these *missing* fish?

Perhaps it is possible to understand something of sockeye salmon biology and/or sampling at sea by considering why the ratio is >>1.0 when it should be <1.0. One explanation is the possibility that there is differential tagging mortality; i.e., catching an immature sockeye salmon on the high seas (~35 cm fork length) and tagging it induces a ~100-fold increase in mortality compared with catching and placing a tag on a maturing individual (~55 cm fork length). The next idea is that mature and immature fish have different spatial distributions (including depth). Floating longlines are baited hooks that dangle 1 m below the surface of the ocean. If maturing fish are migrating nearer to the surface at twilight (when the gear is deployed) than the immature fish, the gear would tend to encounter more mature fish. Another possibility is that the hooks and bait sizes are selective[80, 108]. The limited recoveries of tagged immature fish suggest a more southerly and westerly distribution of Fraser River sockeye salmon in the Gulf of Alaska but with considerable overlap with maturing fish. Another possibility for the prevalence of maturing fish in the recoveries is the behaviour of maturing fish toward the gear. The caloric requirements of growth, maturation, and migration must be significantly greater than those of growth alone. The bait (salted anchovy/herring) provides a near-surface food for the migrants that is, perhaps, of less interest to the immature fish. Recall that immature sockeye salmon that were caught by gillnets in the Gulf of Alaska in 1958 had relatively little in their stomachs compared to that found in the maturing fish[58].

4.2 Diet and Feeding of Maturing Fraser River Sockeye Salmon

The first assessment of the stomach contents of maturing sockeye salmon was conducted in the summer of 1958[58]. The stock of origin of these fish is unknown, but as the 1958 return of sockeye salmon to the Fraser River was one of the largest of the 20th century, it is not unexpected that some of the fish sampled will have Fraser River origins. Sockeye salmon were identified as either immature or maturing based on a visual inspection of the gonads. The sockeye salmon was the only species of five examined (others included chum, coho, pink, steelhead) to show a significant difference in stomach contents based on the state of maturity. Maturing fish had a greater incidence of squid in the stomach than immature fish. The stomach contents of maturing sockeye salmon were predominantly euphausiids, squid, and fish[58].

In the Subarctic Current region of the Gulf of Alaska (47–51°N, 145°W and 165°W) stomach contents analysis (% weight or volume) found that the major taxa were: euphausiids, copepods, amphipods, crustaceans, squids, pteropods, fishes, polychaetes, chaetognaths, gelatinous zooplankton, miscellanious other animals, and unidentified material. A stomach content index (SCI) was calculated as SCW/BW × 100 (SCW: stomach content weight, BW: body weight). Fork length data were obtained from the Hokkaido University HUFODAT database. Stomach contents data were taken from LeBrasseur[58], Pearcy et al.[83], Kaeriyama et al.[84], and previously unpublished data from M. Kaeriyama for 2003–2006.

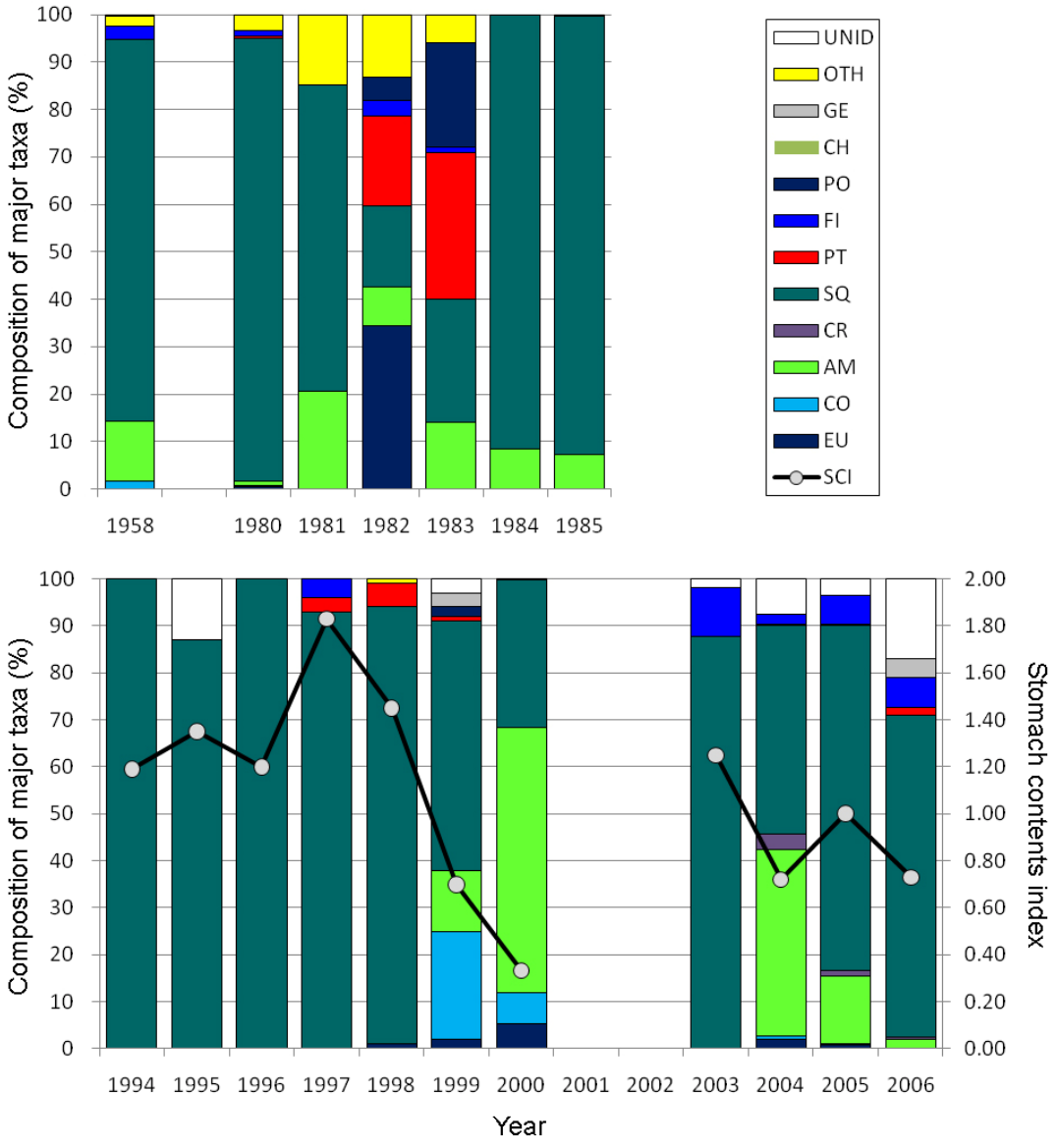

Figure 32: Composition of stomach contents of sockeye salmon caught in the Gulf of Alaska (Subarctic Current) and the trend in the Stomach Contents Index (see text for definition).

Over many years, the gonatid squid (*Berryt0euthis anonychus*) was generally the dominant prey of sockeye salmon collected at the Subarctic Current area in the Gulf of Alaska (Figure 32). This is consistent with the generally southern locations of these samples in the Gulf of Alaska. LeBrasseur[58] reported that the proportion of squid decreased and the proportion of fishes in the diet increased at the Alaskan Stream to the North. The fraction of squid in the sockeye salmon stomachs was positively correlated with the SCI (Figure 33). Although the proportion of squid in the stomachs did not have temporal trend, it was less than 50% in 1982, 1983, 2000, and 2004 (Figure 34), suggesting that feeding conditions were suboptimal in these years.

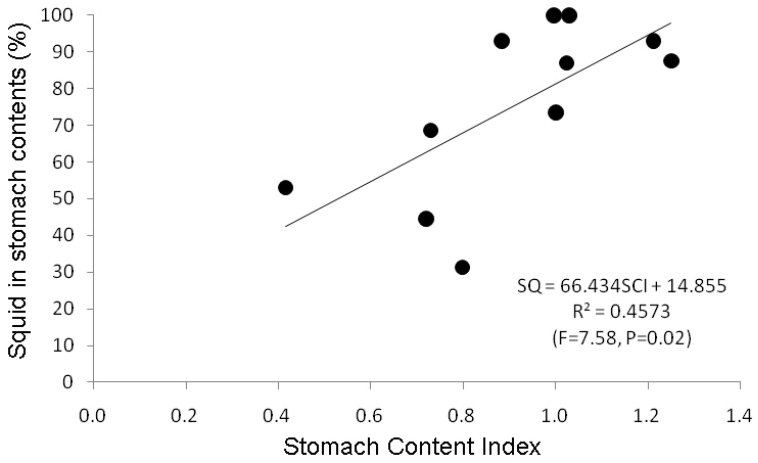

Figure 33: Percentage of squid (by weight or volume) in the stomachs of sockeye salmon caught in the Gulf of Alaska in summer, 1980–2006 and 1958 versus Stomach Content Index (see text for description).

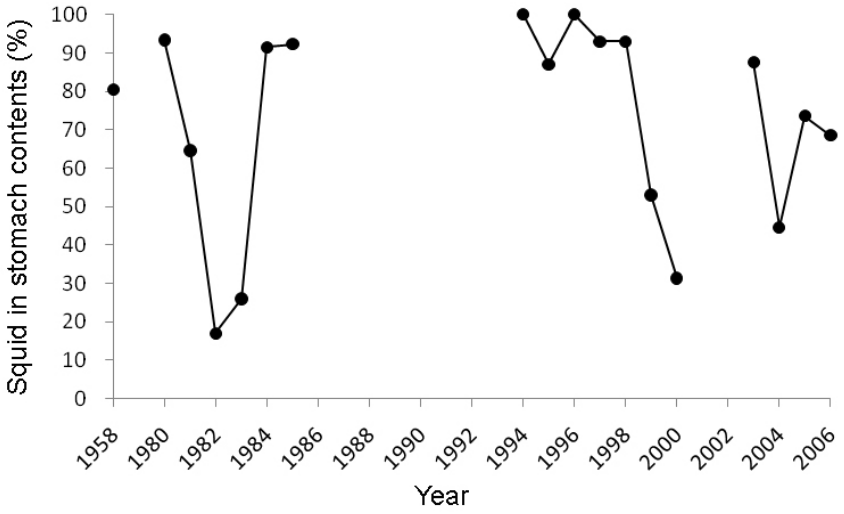

Figure 34: Percentage of squid (by weight or volume) in the stomach contents of sockeye salmon caught in the Gulf of Alaska by year.

4.3 Growth of Maturing Fraser River Sockeye Salmon

"Yet it is only by tracing fluctuations in the growth of the individual from season to season that we can hope to ascertain whether such fluctuations can be correlated with each other, or with any external factors, and can also ascertain what, if any, regulatory mechanisms are involved."

Charles Henry Gilbert, 1914

4.3.1 Average size at age

At the beginning of the 20th century, it was understood that fish growth is the increase in mass (weight) of an individual fish with the passage of time, and that external factors might influence that process. It is rarely observed in nature. Occasionally, fish are tagged or marked as juveniles with marks that can be distinguished at recapture. If the mass at tagging and mass at recapture were recorded by the researchers, a measure of growth can be obtained for the interval of time that the fish was at large. In general, these data are never measured with sufficient frequency during a fish's life to understand the details of an individual salmon's growth, but there have been times, in the past, when the average mass of maturing salmon was measured routinely within some rivers.

The weights of individual maturing salmon were measured routinely (as was fork length) at canneries in the major sockeye salmon rivers of B.C. (Fraser, Rivers, Skeena, Nass) by agents of the Province of British Columbia from 1913 to 1924 and the Biological (Fisheries) Board of Canada from about 1925. When the IPSFC was established in 1937, responsibility for biological measurements for the Fraser River was transferred to the new Commission. Routine measurement of sockeye salmon body weight and fork length were continued in the other major rivers (Smith Inlet replaced Fraser River) by the Board until the early 1970s when these responsibilities were transferred to biologists employed by the federal government department responsible for fisheries. Routine measurements of body weight of individual salmon diminished in the 1970s, and as a consequence, most contemporary studies of fish growth have considered only fish length (more easily measured) rather than mass. It is possible to obtain a reliable detailed measure of an individual fish's growth from the ring-like increments recorded in an otolith or fish scale[87], but this is (currently) a labour-intensive process that few agencies undertake as routine practice. Therefore, growth of sockeye salmon is assessed currently by examining the mean lengths of a population or a group of populations.

The mean fork length of Fraser River sockeye salmon caught in the fisheries has been reported routinely since the early 1900s[2]. However, stock-specific measurements of fish escaping the fishery to the spawning grounds have been measured relatively consistently only since the 1950s. The fork lengths, computed as anomalies from the long-term age- and stock-specific average of stocks with the lengthier time series are shown in Figure 35. The grand means (average of mean values) of age-1.x smolts are: age-1.1(39.8 cm), age 1.2 (54.2 cm), and age-1.3 (59.2 cm). Prior to the 1950s, the grand mean of age-1.2 sockeye salmon caught from 1914 to 1956 was 60.1 cm. The difference of –5.9 cm between the two periods (1914–1956) versus (1950–2009) may be the greater influence of gillnet selectivity, in addition to factors associated with abundance.

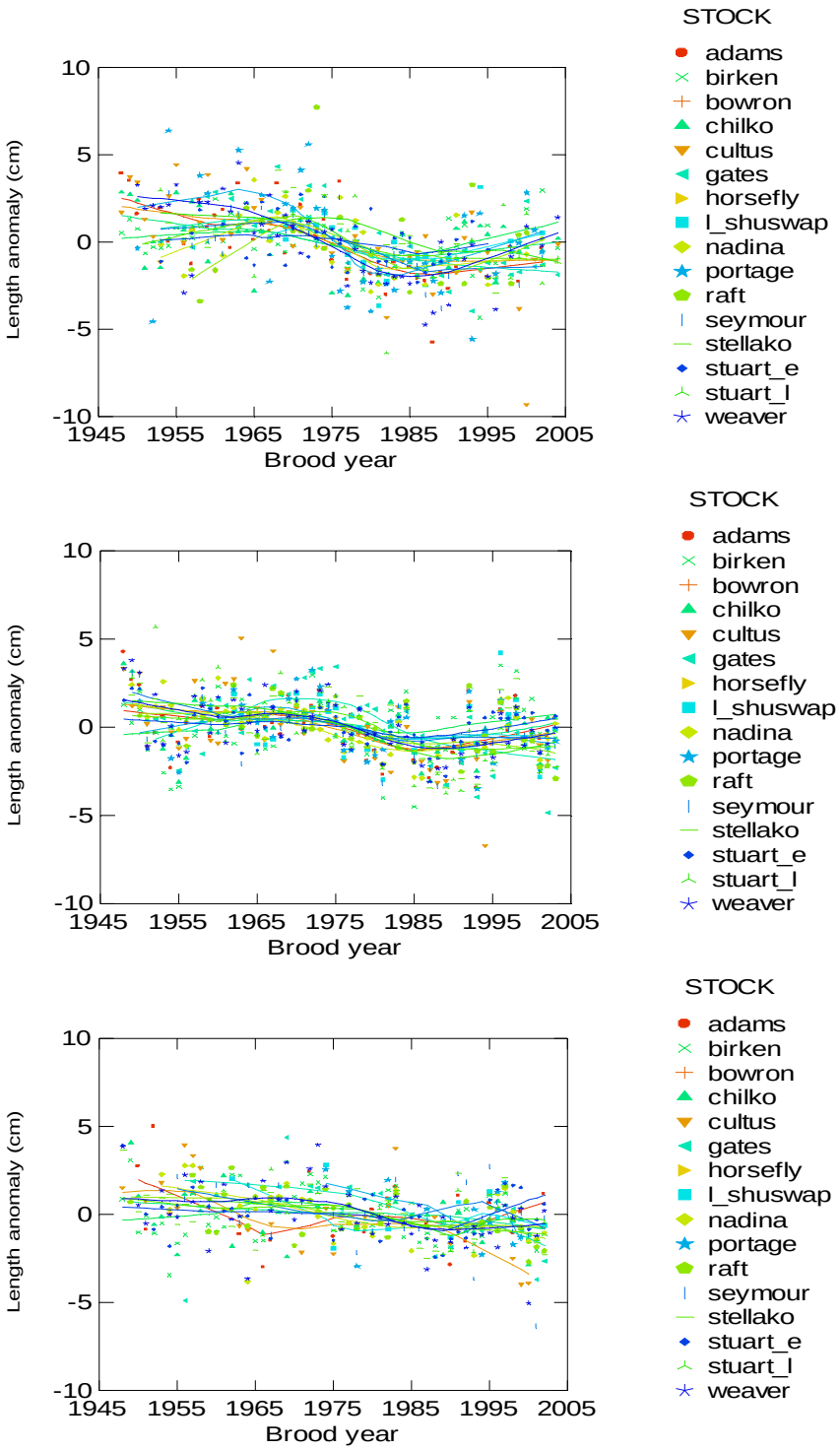

Figure 35: Mean fork length anomalies (cm) for 16 populations with longer time series measurements for age 1.1 (upper), 1.2 (middle) and 1.3 (lower) panels. Each anomaly was computed by subtracting the long-term average, for each age and population, computed over the entire time series. The male and female fork lengths were averaged.

In what must have been one of the first biological samples of sockeye salmon size taken on the Fraser River, Charles H. Gilbert measured the sex and length of a sample of 500 fish collected from August 2–4, 1911[109]. He had just established a reliable method of determining fish age from the rings on their scales, and this was an essential prerequisite to measuring growth. Older sockeye salmon tend to be larger, but it is not diagnostic; there is considerable overlap in the size frequencies of each age-class[109]. Therefore, it was necessary to understand whether a change in mean size from year to year was a consequence of interannual variations in growth, or simply a change in the age composition. A sample of sockeye salmon with more age 1.3 fish, for example, will tend to have an average mean size that is greater than a sample with greater fraction of age 1.2 fish. The mean lengths of males in 1911 were: age 1.2 (65.0 cm, +10.2 cm), age 1.3 (67.1 cm, +7.9 cm) and of females were: age 1.2 (62.7 cm, +8.5 cm) and age 1.3 (65.9 cm, +6.7 cm). The signed values in parentheses indicate how much larger the mean values were in the 1911 sample. Some of the difference can be attributed to Gilbert's method of measuring fork length using a tape placed along the body of the salmon so the curvature of the body gives a slightly longer measure of length than that obtained by contemporary measuring boards, but this will be a relatively small adjustment.

4.3.2 Trends

From 1952 to 1993, there was a significant linear trend (decrease) in mean size at maturity of 10 Fraser River stocks and the trend, it was felt, was due to increasing surface temperatures affecting sockeye salmon metabolism on the return migration[110]. Mathisen et al.[111] used a subset of return years (1973–2000) and found that there was no significant linear trend in mean size of Cultus Lake, Adams River, and Chilko Lake populations, but significant declines in mean length were observed in the Nadina and Stuart stocks. However, when a more comprehensive view of the time series is considered (1952–2009 return years), it becomes evident that there is significant low-frequency variability in mean size (fork length) (Figure 35) that is not a simple linear trend.

The grand mean fork length (across stocks) of age 1.1 jacks was above average up to the 1976 brood year (1979 return year). It dropped abruptly in the 1977 brood year, returned to average for the 1978 brood year and then remained below the long-term average until the present, except for the 1984 brood year when it was slightly above average. The 1977 brood year went to sea in the spring of 1979 and returned in the summer of 1980, so this was the first anomalous year for marine growth. Since the 1977 brood year, the overall trend in the grand mean has been positive.

The grand mean fork length of the more abundant age 1.2 sockeye salmon was near the long-term average in the early 1950s and increased through the mid-1970s to the largest mean fork length in the time series. The first appearance of an abrupt decline in mean fork length occurred in the 1976 brood year which entered the ocean in 1978 and returned to spawn in the summer of 1980. These years coincide with the return year of the first appearance of smaller than average age 1.1 jacks. A reasonable hypothesis for the coincident appearance of strongly smaller than average Fraser River sockeye salmon in two different brood years is that they were both affected by the 1979/80 ocean environment. The reduction was greater in age-1.1 than in age-1.2 sockeye salmon; the latter returned to near the long-term average for the late 1970s to mid-1980s when the mean fork length declined further.

From the mid-1980s, the grand mean fork length of age 1.2 sockeye salmon increased but was highly variable. In some years (1992, 1996) the grand mean was as large as the highest values seen in the mid-1970s. The general tendency from 1952 to 1993 was for Fraser River sockeye salmon to return at smaller mean size in years when the Gulf of Alaska surface waters are warmer[110]. A similar correlation sign was evident in subsequent data (Figure 36) but the month of June has the strongest correlation during the recent period. The reason for the highest correlation appearing in the area of the California Current upwelling zone is unknown but it may be a result of the relatively short duration of the time series.

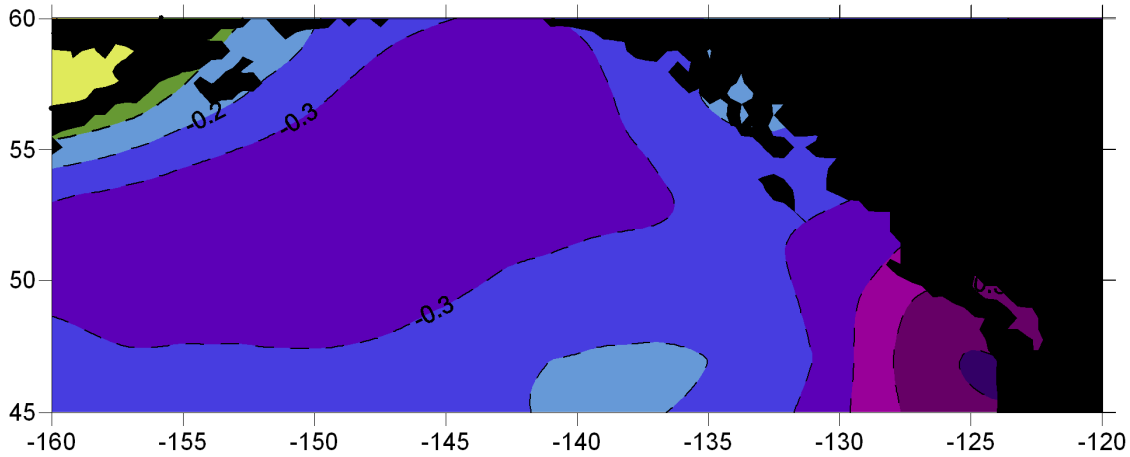

Figure 36: Contours of correlations between a grid of June SSTs in the Gulf of Alaska with the annual grand mean length of Fraser River sockeye (pooled across 16 stocks and sex) from 1993–2007. Contour intervals are 0.1 and negative values are indicated by a dashed line. SST data are NOAA's Extended Reconstructed SSTs on a 2° lat./long. grid. June exhibited a significantly stronger correlation of SST with length than the previous 5 months.

The grand mean fork length of age-1.3 sockeye salmon is more variable with a generally declining trend. The first noteworthy decline in mean size from previous years appeared in the 1975 brood year that went to sea in 1977 and returned to spawn in 1980. The observation of much lower mean fork length is shared among these three cohorts which share a common year of maturity. The grand mean fork length of age 1.3 sockeye salmon has tended to be below average since the mid-1970s brood year. The lowest values in the time series occurred in the 2000 and 2001 brood years.

4.3.3 Density-dependent growth (intra-specific)

> *"If competition in the sea with members of their own race exercises any influence on stature, this should become evident where the annual runs oscillate so extensively as they do on the Fraser. There is widespread impression that the fish of the big runs average smaller than those of other years, and canners generally assert that the fish run more to the case in the big years than at other times."*
>
> Charles Henry Gilbert, 1914

Gilbert's thoughts about variation in the average size of maturing Fraser River sockeye salmon in relation to their own abundance continues to attract the interest of scientists working nearly a century later. The fascination must, at least in part, be related to the conclusion that follows from this observation; that the sea provides only limited amounts of food for growing sockeye salmon. Bristol Bay sockeye salmon were also found to have a smaller mean size when they were more abundant (Rogers 1980). Fraser River sockeye salmon were found to be smaller when the total abundance of sockeye salmon in the Gulf of Alaska was greater[112], but it was not a universal truth. In central and northern B.C., a density-dependent effect on mean size appeared only in age 1.3 sockeye salmon but not in age 1.2[89]. The difference was attributed to differences in the temporal/spatial patterns of the two age-classes in the Gulf of Alaska.

Considering how gross measures of sockeye salmon abundance in the Gulf of Alaska might affect average fork length of certain stocks may be appropriate if all stocks are broadly distributed in the Gulf of Alaska, but there are some interesting within-stock patterns in mean length and abundance. The Adams River population, for example, shows no significant relationship between the annual returns of age-1.2 fish and their mean fork length, in spite of annual returns that can vary over three orders of magnitude up to 20 million. Chilko Lake, on the other hand, has significantly smaller mean fork length in age-1.2 fish in years with its highest returns and these do not exceed five million. Furthermore, marine survival is reduced at what is considered a high return abundance for this stock. One is left with an impression that the Adams River population has an oceanic behaviour which allows all of its members to reach a fork length that is not affected by the population's own abundance, while the Chilko Lake stock has an oceanic behaviour that does not produce a similar result. When considered across all 16 stocks described in Section 4.3.2, an analysis of covariance indicated that, while mean fork length differed significantly among stocks ($P < 0.001$), there was no statistically significant general influence of within-stock abundance. Apart from Chilko Lake, the Gates and Late Stuart stocks were the only other stocks showing a significant abundance-related effect on mean length in age 1.2 returns.

As has been found commonly in other B.C. sockeye salmon stocks[88, 89], the mean length of the age-1.3 ecotype was highly positively correlated with that of the age-1.2 ecotype returning in the same year (Figure 37), but not correlated with the mean length of its sibling age-1.2 ecotype that matured one year earlier. This provides strong evidence that mean length at maturity is determined in the final year at sea. Stock-specific differences in mean length and co-maturing age-1.2 mean length explain 75% of the variation in mean length of the age-1.3 ecotype. As was found in the age-1.2 ecotype in Chilko Lake, the mean length of the age-1.3 ecotype in Chilko Lake was also significantly smaller ($P < 0.05$) when returns that accompanied it were high. As was observed in the previous paragraph for the age-

1.2 ecotype in the Adams River, the mean length of the age-1.3 ecotype was also independent of the Adams River return abundance.

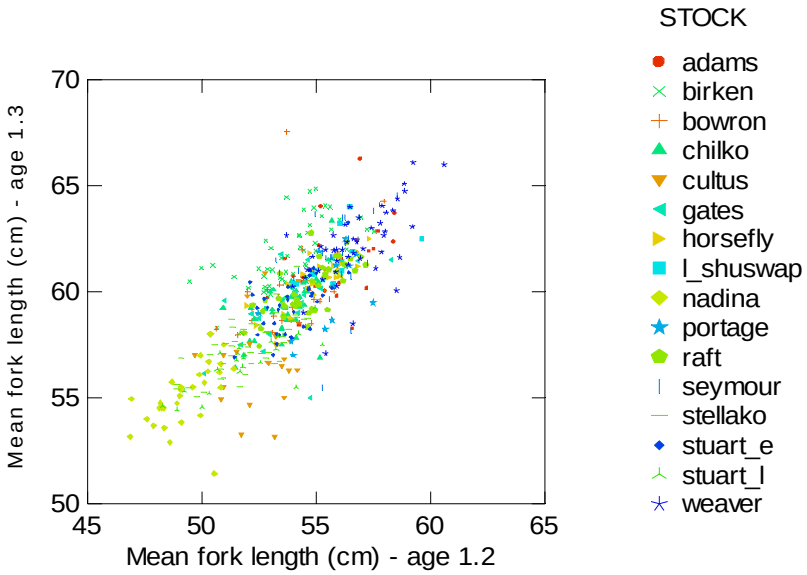

Figure 37: Mean fork length (cm) of age-1.3 ecotype of sockeye salmon in year x versus mean fork length (cm) of age-1.2 ecotype of the cohort in year x + 1. These ecotypes mature and return to spawn in the same year.

Until the mid-2000s, the T/V *Oshoro-maru* conducted annual cruises in summer to the Gulf of Alaska. Cruise tracks were typically, but not always, N–S transects along 145°W longitude. Each night while on station, a multi-mesh gillnet was set to obtain biological samples of salmonids. Fork lengths of the sockeye salmon caught in these surveys were recorded by sex and age. From 1980 to 2000, fork length did not have a temporally varying cycle or trend by sex and by age (Figure 38). This may reflect the composite multi-stock nature of these samples. As the data include only the period after 1980, it may not reflect the long-term pattern that is evident in samples taken of Fraser River sockeye salmon (Figure 35).

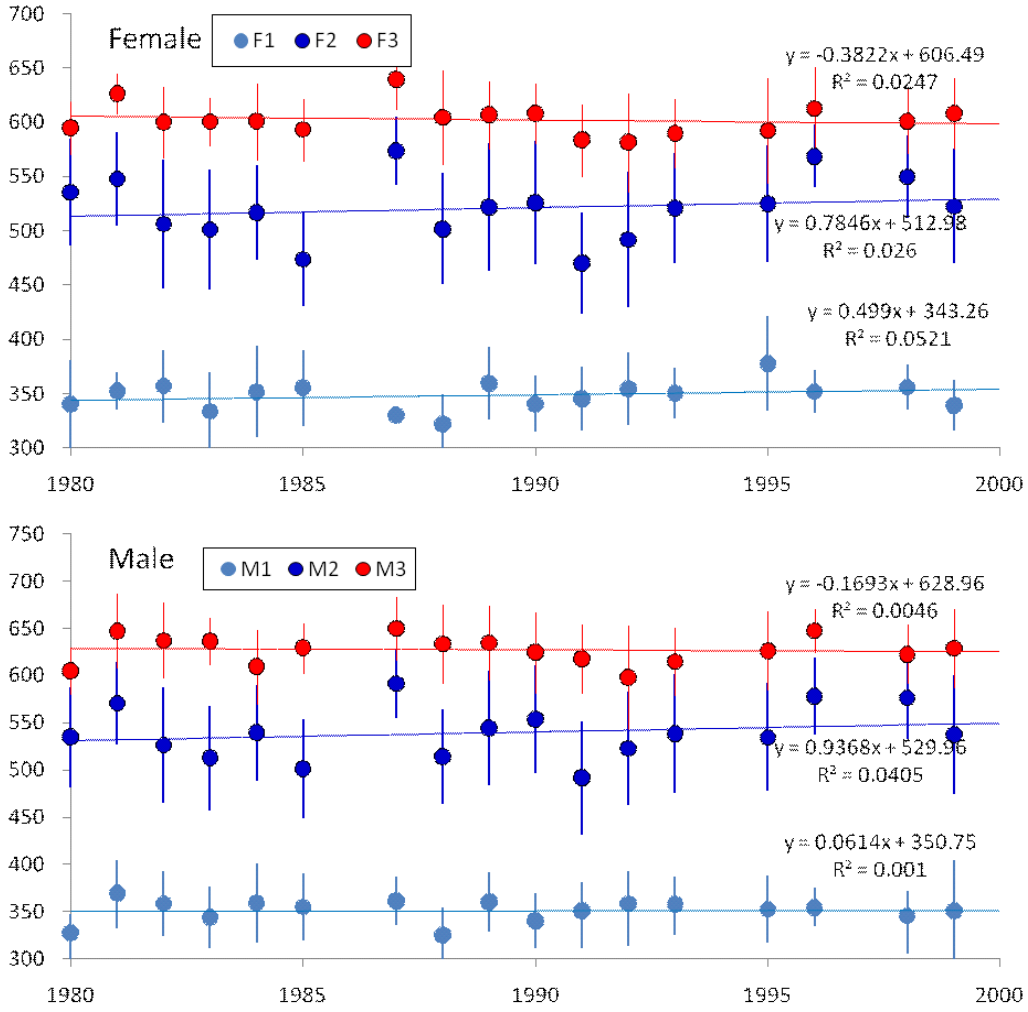

Figure 38: Mean and standard deviation of sockeye salmon fork length, by sex and ocean age (M1 = age x.1, M2 = age x.2, and M3 = age x.3), of sockeye salmon caught by gillnet in the Gulf of Alaska along 165°W and 145°W. Linear trend fits are indicated for each. None were statistically significant.

4.3.4 Density-dependent growth (inter-specific)

When the ANCOVA described in Section 4.3.3 is repeated to include potential differences in mean fork length in odd/even years, it was found that the mean fork length of age-1.1 Fraser River sockeye salmon jacks was significantly smaller ($P < 0.05$), by 4 mm, in brood years that matured in odd years. Likewise, the average fork length of age-1.2 sockeye salmon maturing in odd years was significantly smaller ($P < 0.001$), by 8 mm, than age-1.2 sockeye salmon maturing in even years. Finally, the average fork length of age-1.3 sockeye salmon maturing in odd years was significantly smaller ($P < 0.05$), by 3.5 mm, than age-1.3 sockeye salmon maturing in even years.

As the odd/even cycle of abundance of pink salmon (*O. gorbuscha*) to the Fraser River is potentially a source of competition for Fraser River sockeye returning the same year, it is normal to consider that a reduction in mean size in odd years is a consequence of competition for food with pink salmon during the period of overlap in the Gulf of Alaska. Presumably, the competition arises from the interactions of maturing sockeye salmon and maturing pink salmon as the two groups do not likely share a common habitat until the pink salmon move off the continental shelf into the Gulf of Alaska.

If the biannual effect on maturing Fraser River sockeye salmon growth is due to maturing Fraser River pink salmon, the tagging data suggest that it must occur late in life because the high seas distribution of maturing sockeye salmon bound for the Fraser River is very different in time/space from that of Fraser River pink salmon (Figure 39a). It would seem, therefore, that the greater potential for the mean length of Fraser River sockeye salmon to be lower in odd years is due to competition with a greater overall abundance of pink salmon in Alaska and its biennial cycle (Figure 40).

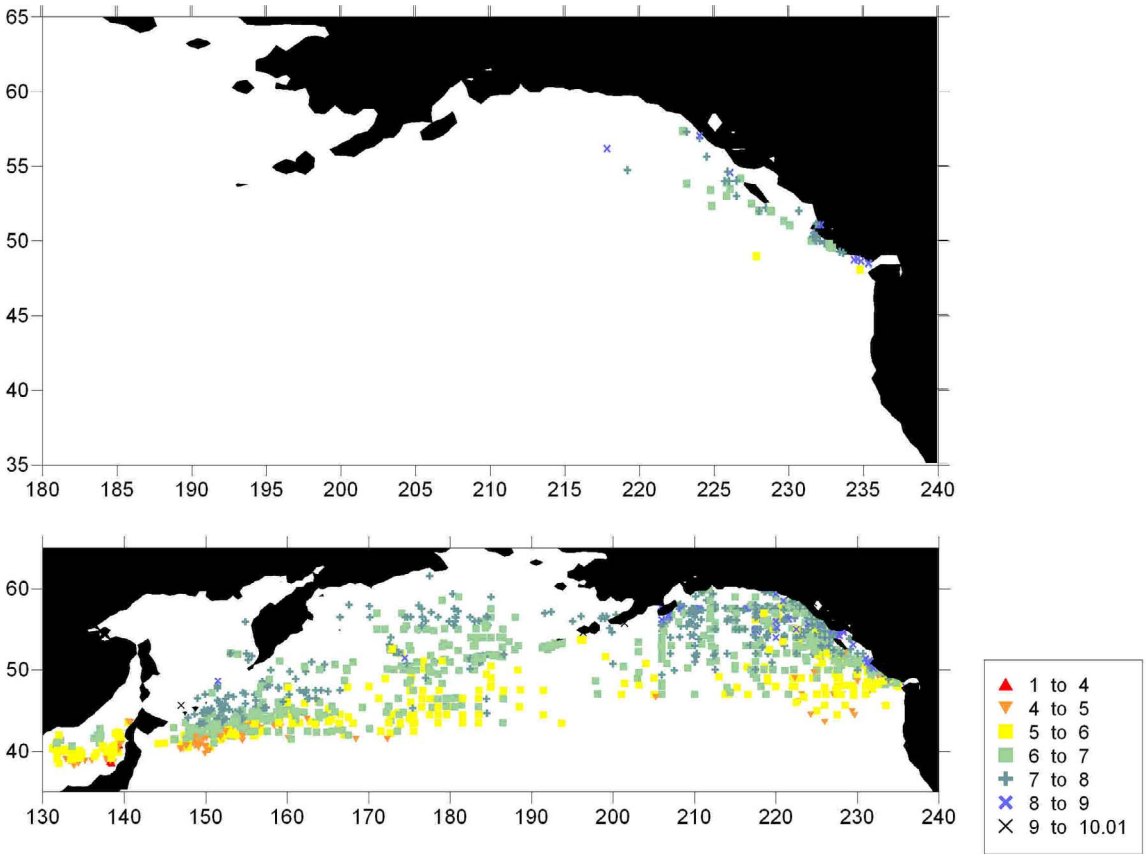

Figure 39: (Top panel) Release locations of pink salmon that were tagged on the high seas and recovered in odd years in Fraser River salmon fisheries (same general recovery areas selected for sockeye salmon in Figure 17) compared to (bottom panel) the distribution of tagging locations of pink salmon[68]. Plot symbols indicate month of tagging.

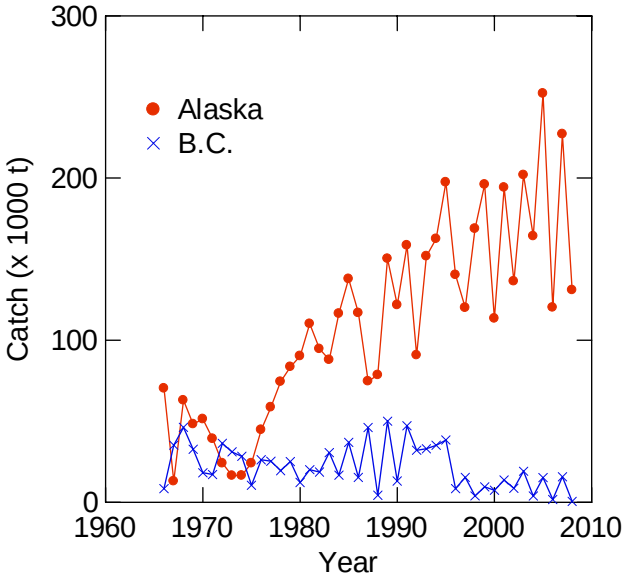

Figure 40: Catch of pink salmon in Alaska (Southeast and Central) and British Columbia (includes Washington). Data from Irvine et al.[113].

Ruggerone et al.[114] found a similar interaction between Bristol Bay, Alaska sockeye salmon growth and Russian pink salmon abundance. The competitive effect of pink salmon abundance is not always expressed at this life history stage, as it has appeared at different life history stages[115] and with varying degrees of influence. In Puget Sound, for example, pink salmon abundance appears to influence survival. The survival of hatchery releases of chinook salmon into Puget Sound was 59% lower for cohorts that were released in even years from 1984 to 1997[116]. Juvenile pink salmon, especially from the Fraser River, are orders of magnitude more abundant in even years in the Salish Sea (Strait of Georgia + Puget Sound) than in odd years.

An analysis of covariance of mean annual fork length (males and females averaged) of maturing age-1.2 Fraser River sockeye salmon stocks, from Figure 35, was used to examine correlations between mean fork length and coarse indicators of maturing Gulf of Alaska salmon abundance. Covariates were total Gulf of Alaska pink salmon catch, total Gulf of Alaska sockeye salmon catch, and total western Alaska sockeye catch. It was found that all three catch totals were statistically significant ($P<0.001$) but the coefficients (relative influence on mean fork length) were largest for total Gulf of Alaska sockeye and least for Gulf of Alaska pink salmon catch. These covariates "explained" 70% of the interannual variation in Fraser River sockeye salmon mean length. The difficulty attributing catch (related to abundance) as the cause of the variation is that all catch time series and the mean length time series have a strong component of low frequency that may have arisen spuriously, and the catch time series are correlated with each other (Figure 41). The low frequency component of variation in mean fork length seems, rather generally, to follow as an inverse of the commercial catch of sockeye salmon in the Gulf of Alaska. Larger Fraser River sockeye salmon and smaller catches are found in the early part of the time series, followed by smaller sockeye salmon and larger catches in the mid-period, by increased mean length and lower catches of sockeye salmon in the Gulf of Alaska in the latter part

of the series. For unknown reasons, the mean length of age-1.2 Birkenhead sockeye salmon was uncorrelated with these catches but 13 other stocks had negative slopes.

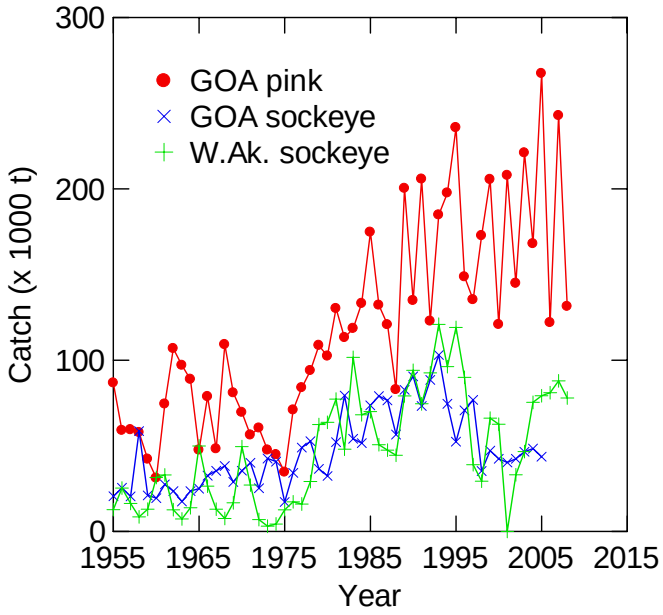

Figure 41: Total commercial catch pink salmon and sockeye salmon (tonnes × 1000) in the Gulf of Alaska and total catch of sockeye salmon in western Alaska from 1955 to 2008. Data from Irvine et al.[113].

Without considering population-specific differences in growth rates, Ishida et al.[82] in their review of growth of Pacific salmon, found that growth rates of maturing sockeye salmon, pink salmon, and coho salmon were higher than those of immature fish of the same age. They considered that life-history stages with higher growth rates and higher food requirements would provide conditions that would allow for density-dependent growth.

Summary – For more than a century, it has been recognized that the average size of sockeye salmon returning to the Fraser River varies from year to year. Overall, the mean fork length at maturity of age-1.1, 1.2, and 1.3 Fraser River sockeye salmon is independent of the abundance of the Fraser River cohort that survives to maturity. An exception appears to be Chilko Lake where the mean fork length of age-1.2 returns is negatively correlated with its abundance.

4.4 Migration Behaviour and Timing

"There is no evidence that fish can navigate in the open waters."

Wilbert A. Clemens, 1951

4.4.1 Depth of migration

The first applications of data storage tags to maturing sockeye salmon in the Gulf of Alaska were conducted by the Fisheries Research Institute of the University of Washington. These tags recorded ambient temperatures and pressures (depths) experienced by the fish at frequent intervals. There are no recoveries of Fraser River sockeye salmon with these tags, but the behaviour of a maturing fish that was recovered at the mouth of the Taku River (Southeast Alaska) confirmed some previous ideas about their migration depth. The median daily depth was routinely <10 m (Figure 42). Only on the day of tagging was the median value >10 m. Excursions by the fish to deeper, colder waters were infrequent. This result has some similarities and some differences to what was observed with ultrasonically tagged Fraser River sockeye salmon in 1985. Quinn and terHart[117] also observed a strong near-surface migration depth after the day of tagging in Queen Charlotte Strait, but the depth of migration deepened as the fish moved from that observed in the well mixed regions of Johnstone Strait/Discovery Passage into the stratified warmer and fresher waters of the Strait of Georgia.

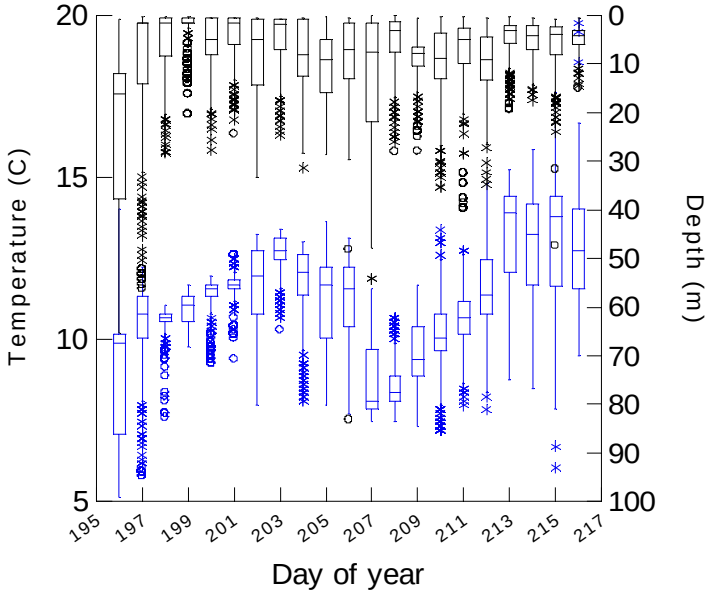

Figure 42: Box and whisker plots of daily variation in depth (m), and temperature (°C, blue) of a sockeye salmon tagged with a data storage tag, from its release in the Gulf of Alaska (55° 10' N 145° 04' W) in July 1999 until its recapture three weeks later in a fishery in the Taku River (Southeast Alaska). The horizontal line within each vertical box indicates the median value over a 24-h period, and the extremes of each box indicate quartiles. Outliers (x) and strong outliers (∘) within each day appear at deeper/colder locations. Data courtesy of the Fisheries Research Institute, University of Washington[118].

4.4.2 Migration timing

The common practice is to estimate, from available sources of run timing information, the date of the peak of the run in Area 20 (western end of Juan de Fuca Strait). The temporal pattern of sockeye salmon abundance during the return migration is a key uncertainty at the beginning of each fishing season. The uncertainty arises in-season because, in different years, abundance in the test fishery does not necessary reflect the abundance of the run until after the peak of the run has passed and its timing that year becomes understood. In different years, the same abundance can be an indicator of a weak, average or a strong run.

Blackbourn[102] reported a tendency for the return timing of seven Fraser River sockeye salmon stocks or stock groups and one sockeye salmon stock in Washington State (Quinault Lake) to be later during years in the Gulf of Alaska when SSTs were warmer. In contrast, he found that the return timing of many northern sockeye salmon populations (Skeena, Copper River, Upper Cook Inlet, Chignik River) was early in warm years. This led him to develop a "displacement" hypothesis where warmer SSTs in the Gulf of Alaska restricted the distribution northward and cooler temperatures allowed a more southerly distribution that put Fraser River sockeye salmon closer to the Fraser River at the onset of migration. The ocean temperatures providing the greatest explanatory power were found to be those of the winter and/or spring immediately preceding their return to the Fraser River.

With the passage of more than 20 years, it is possible to test this hypothesis with additional data for at least some of the stocks. For Early Stuart, for example, the correlation of peak date with monthly SST in the NOAA Extended Reconstructed SST database (2° lat./long. grid), for the period 1985 to 2010 was r = +0.76, but the maximum correlation occurred in spring (April/May) rather than the previous December reported by Blackbourn[102]. Changes of a few months in these correlations are not entirely unexpected because of the autocorrelation in seasonal SST. The peak correlation was found near Ocean Station P (45°N 145°W), approximately the same location reported by Blackbourn[102].

Estimates of the peak date of return through Area 20 from the 1950s to the present for Chilko Lake sockeye salmon are more variable (Figure 43). Some of this variation may be due to co-migration with other Summer-run stocks and the need to use stock identification techniques to determine the proportion of Chilko Lake fish in the catch. The Early Stuart run is sufficiently early so that it does not have this additional source of observation error. Low frequency variability in Chilko Lake run timing is evident in Figure 43; largely due to later-than-average return dates in the early 1990s. The trend has been earlier for the most recent decade, with a noteworthy outlier in 2005 that most runs to the Fraser River experienced.

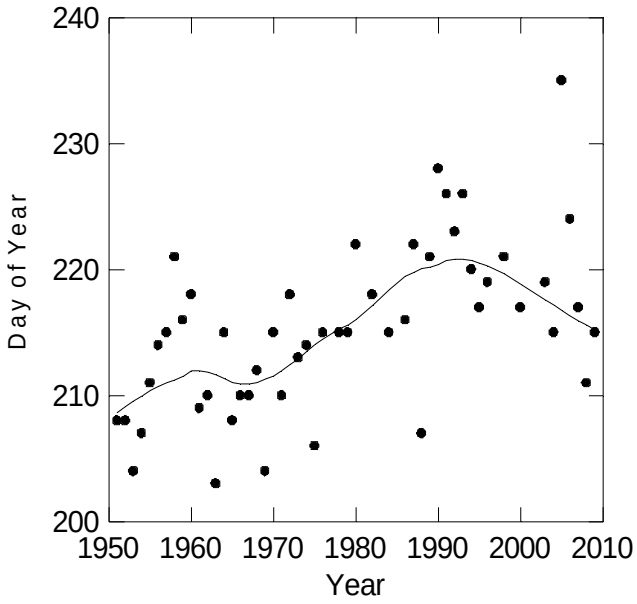

Figure 43: Date of 50% return of maturing Chilko Lake sockeye salmon through DFO Statistical Area 20 (western Juan de Fuca Strait) from 1950 to present. Data since 1980 are based on run reconstructions by the PSC.

Using a more conservative test of hypothesis than Blackbourn[102], Hodgson[119] confirmed that the run timing of Fraser River populations, except Pitt and Adams, tended to be earlier after cold spring-summer periods and later following warm periods. Likewise, populations from the Cook Inlet, Kodiak Island (except Ayakulik), Alaskan Peninsula and Bristol Bay tended to be later following cold April-July periods and early migrations tended to follow warm periods. In populations from Washington State, central and northern B.C., Southeast Alaska and Prince William Sound, there were no consistent relationships with SST within regions.

Daily counts of sockeye salmon migrating past the Docee fence (Long Lake) provide an opportunity to compare Fraser River sockeye salmon run timing with a central coast sockeye salmon population. Peak dates for the Long Lake sockeye salmon returns were calculated (Table 4.4.2) from 1990 to 2009 using a salmon fishery run timing model[120]. During these years, selected only to provide a sample for comparison, the Long Lake sockeye salmon run arrived three weeks earlier, on average, than the Chilko Lake run and 10 days later than the Early Stuart run. Year-to-year variation in timing was positively correlated among these runs, more so with Chilko Lake timing ($r = 0.68$, $P < 0.01$) than with Early Stuart timing ($r = 0.45$, $P < 0.05$). There is no autocorrelation in the Long Lake time series but there is in both Fraser River time series so the Early Stuart correlation is not statistically significant.

Table 4.4.2: Estimates of peak date of sockeye salmon migration past the Docee fence (Statistical Area 20, Long Lake) from 1990 to 2009 based on the method of Schnute and Sibert[120]. All dates are in July; subtract 181 from day of year to find the July date (182 for leap years). Sockeye salmon counts from http://www.pac.dfo-mpo.gc.ca/northcoast/counts/docee/default.htm

Year	Day of Year
1990	209 (July 28)
1991	203
1992	195
1993	202
1994	202
1995	198
1996	197
1997	202
1998	194
1999	204
2000	196
2001	197
2002	196
2003	196
2004	198
2005	206
2006	204
2007	197
2008	197
2009	200

A recent study found that upon reaching the coast, sockeye salmon from Late-run populations (Adams and Weaver Creek) had an average migration rate of approximately 20 km d^{-1} through the marine area and held at the river mouth and adjacent areas for approximately eight days before entering the river and summer-run populations (Birkenhead, Chilko, Horsefly and Stellako) had a migration rate approximately 33 km d^{-1} but they held near the river mouth for only approximately 2 days[121]. Males migrated at higher speed than females through the Strait of Georgia. Successful migrants had the property of delaying briefly before entering the Fraser River, combined with low plasma testosterone, and high somatic energy.

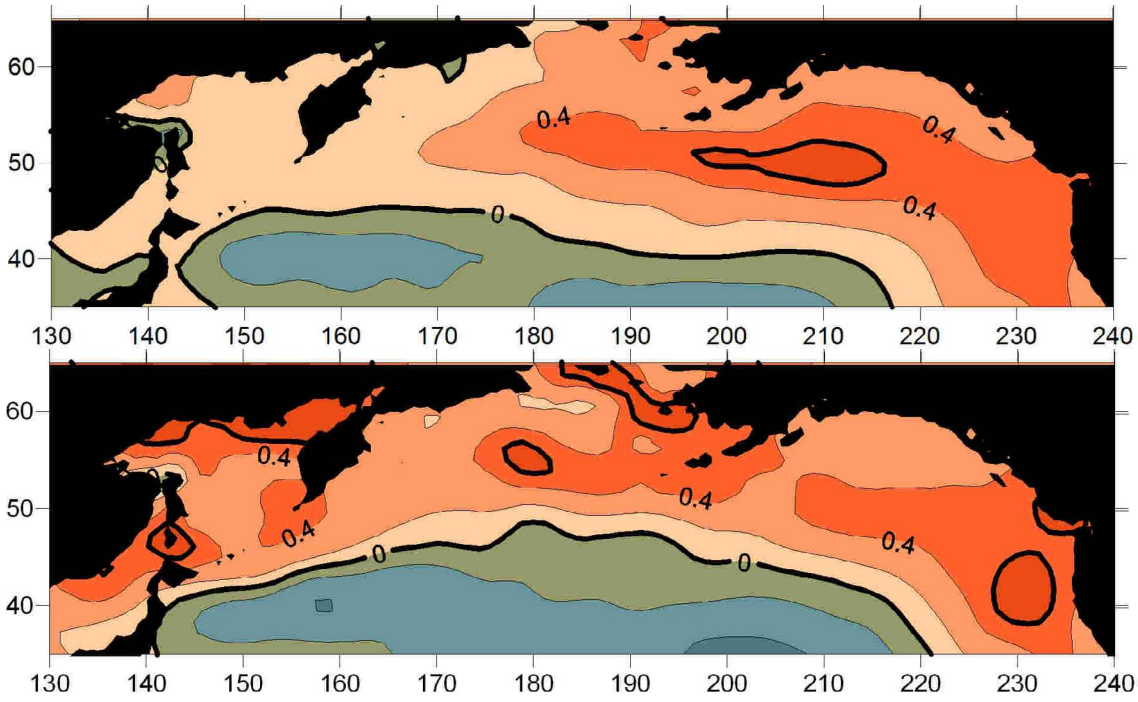

Figure 44: Contours of correlation between date of peak abundance of Early Stuart (upper panel) and Chilko Lake (lower panel) sockeye salmon in DFO Statistical Area 20 versus mean April sea surface temperatures at each 2° × 2° lat./long. grid point in the northern North Pacific. Warmer colours are positive correlations (later arrival when warmer) and cooler colours are negative correlations (earlier arrival when cooler). Contour interval is 0.2 and contours equal to 0.0 and +0.5 are highlighted with thicker lines. Sources: SST data from the NOAA Extended Reconstructed SST database. Chilko Lake dates (1951–2009) from the Pacific Salmon Commission.

Summary – The geographic pattern of correlations between Fraser River sockeye salmon run timing and SST (Figure 44) were developed from >50 years of run timing data. Blackbourn[102] found that a warmer (colder) Gulf of Alaska before the return migration was associated with later (earlier) return timing. This observation has survived the addition of 25 years of additional data. For Early Stuart sockeye salmon, the largest positive correlation between temperature and run timing (r = 0.63) appeared near Station Papa (50°N 145°W), DFO's longstanding ocean/climate research and monitoring site in the Gulf of Alaska. The largest negative correlation (r = –0.51) was located Northwest of the Hawaiian archipelago in March. The broad-scale patterns correlation patterns suggest that return timing is associated with the large-scale climate patterns of the North Pacific Ocean. During the period of record, one of the warmest years in the Gulf of Alaska, 2005, accompanied remarkably late run timing.

4.5 Landfall

The route used by Fraser River sockeye salmon to get from the central part of the Gulf of Alaska to the coast is known only in generality. It has been inferred from the seasonal development of catches along the B.C. coast and from the patterns of catches in high seas studies of the 1960s and 1970s. Healey et al.[122] described two general hypotheses for interannual variation in coastal migration routes. The first has the sockeye salmon following isotherms or other watermass properties that affect the distribution of their prey. The second is that large-scale ocean currents have sufficient influence that they deflect the migration northward in years of stronger circulation in the Alaskan Gyre.

A few modelling studies have addressed issues associated with landfall[123, 124, 122]. Thomson et al.[123] considered the hypothesis that the interannual variability of the Northeast Pacific Ocean circulation affected the latitude of landfall and the migration speed of maturing sockeye salmon returning to the Fraser River. By comparing the years 1982 and 1983 they concluded that large-scale ocean circulation had the potential to affect the migration of Fraser River sockeye salmon. Landfall is a loosely defined term, based on the idea that Fraser River sockeye salmon follow a compass orientation toward the coast until they make landfall at some average latitude which varies from year to year, then follow other cues presented along the coast as they migrate toward the Fraser River.

Coastal test fisheries were established to assess the in-season development of the annual migration. They provide one of the few opportunities to examine year to year differences in migration using standardized methods. The Round Island (Johnstone/Queen Charlotte Strait) and San Juan (Juan de Fuca Strait) gillnet test fisheries operate at the entrances to the approach routes to the Strait of Georgia. They provide daily indices of abundance (CPUE – catch per unit effort) as the run passes each location. Differences between these sites may provide an indication of where the returning sockeye salmon encounter the coast. If, for example, a group of fish made landfall at the latitude of Queen Charlotte Sound, some took the western route around Vancouver Island and some took the eastern route, and migrated at the same speed, they would appear first at the Round Island fishery. This would appear as a lag correlation in CPUE between the two fisheries. If the group of fish first appeared at San Juan, it would suggest a more southerly landfall. If the first part of the run appeared at San Juan and the latter part of the run took the eastern route down Queen Charlotte Strait, the ratio of San Juan:Round Island CPUE would decrease through the season.

To study these trends, a three day running average of sockeye salmon CPUE was computed for each of the two gillnet test fisheries using data from 2000 to 2009. A cross-correlation was then computed between the two series in each year at various daily lags to understand whether the timing that was evident in the abundance index at San Juan led or lagged the timing of the abundance index at Round Island. In each year from 2000 to 2009, the maximum correlation between these two smoothed time series occurred when there was no lag between them, suggesting that the timing of the run occurs simultaneously at both test fisheries (Figure 45). This analysis says nothing about the relative fractions of the run following one route or the other, but it reveals that the timing is the same. Except for the year 2000, there was no significant linear trend in the ratio of CPUE at the two fisheries (not shown), suggesting that the fractions migrating via either route does not change substantially through the season in most years. As these are not population-specific trends, a negative trend in this ratio for one stock might be offset by a positive trend in another but this pattern is not one that is thought to occur in nature.

The contemporaneous CPUE in the test fisheries across all 10 years of fishing examined in this study, suggests that there is no substantial alongshore migration of Fraser River sockeye salmon on the West coast of Vancouver Island (or it is equally northbound and southbound) so that the correlation between the two indices is maximum at zero lag. If landfall was north of Vancouver Island, there should be a several day lag for those migrants to reach the San Juan test fishery compared to those arriving at Round Island.

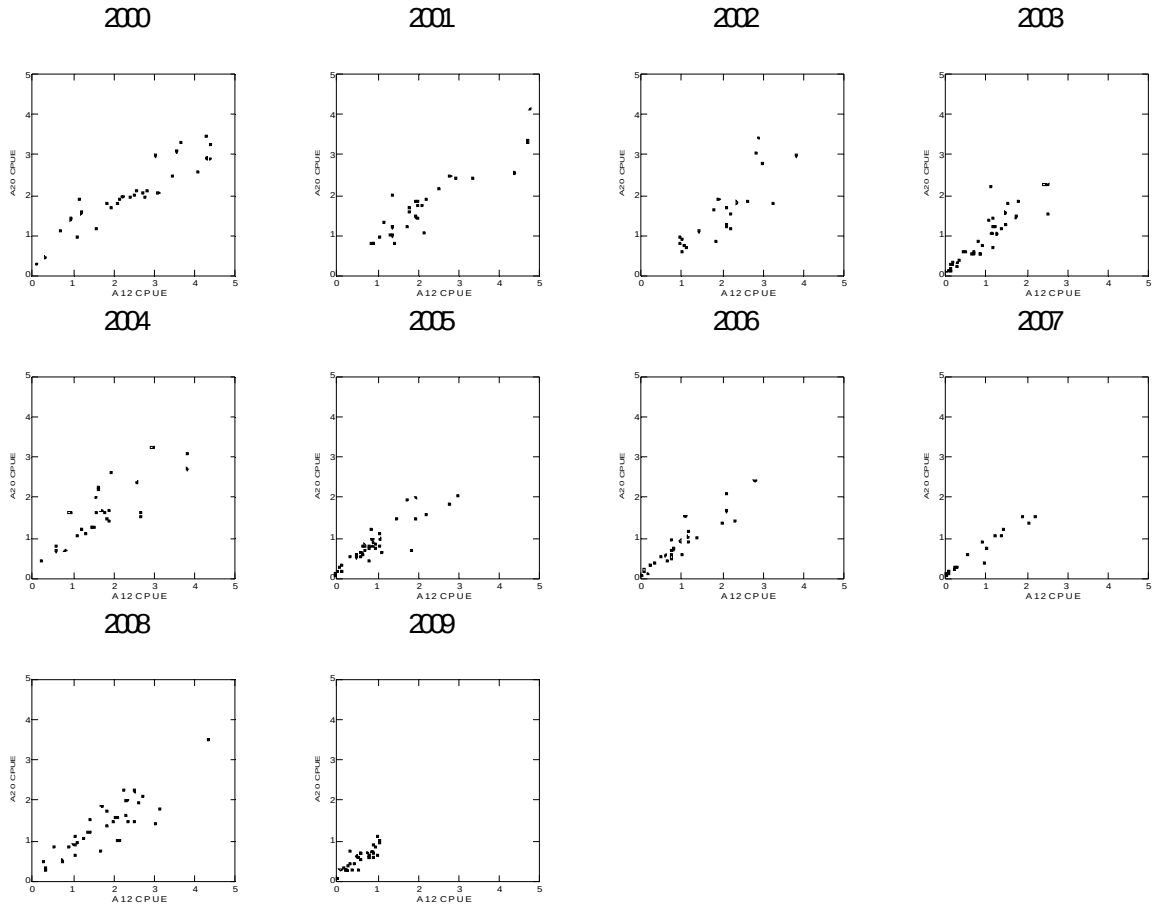

Figure 45: Daily values of the 3-day running mean of sockeye salmon catch per unit effort (CPUE) in the San Juan test fishery in DFO Statistical Area 20 (ordinate) versus the same at Round Island (abscissa) test fishery in DFO Statistical Area 12.

4.6 Northern Diversion

"The small catch [in 1936] in the Strait of Juan de Fuca and in Washington Sound and the large catch in the Johnstone Strait area presented a rather puzzling situation."

Wilbert A. Clemens, 1937

On their homeward migration, sockeye salmon take one of two routes around Vancouver Island to the Fraser River (Figure 46). The average proportion entering the Strait of Georgia via Juan de Fuca Strait was relatively low until 1978 when a rather fundamental change occurred to increase the average proportion of migrants returning via Johnstone Strait[125, 37, 38]. Prior to 1978, only the warmer El Niño years of 1936[126] and 1958[127] elevated the northern diversion significantly above 0.5, although case pack statistics from the canneries in 1937 indicated that modest (21%) northern diversions also occurred[128]. Because the norm was considered to be Juan de Fuca Strait, the fraction returning via Johnstone Strait was called the *northern diversion rate*.

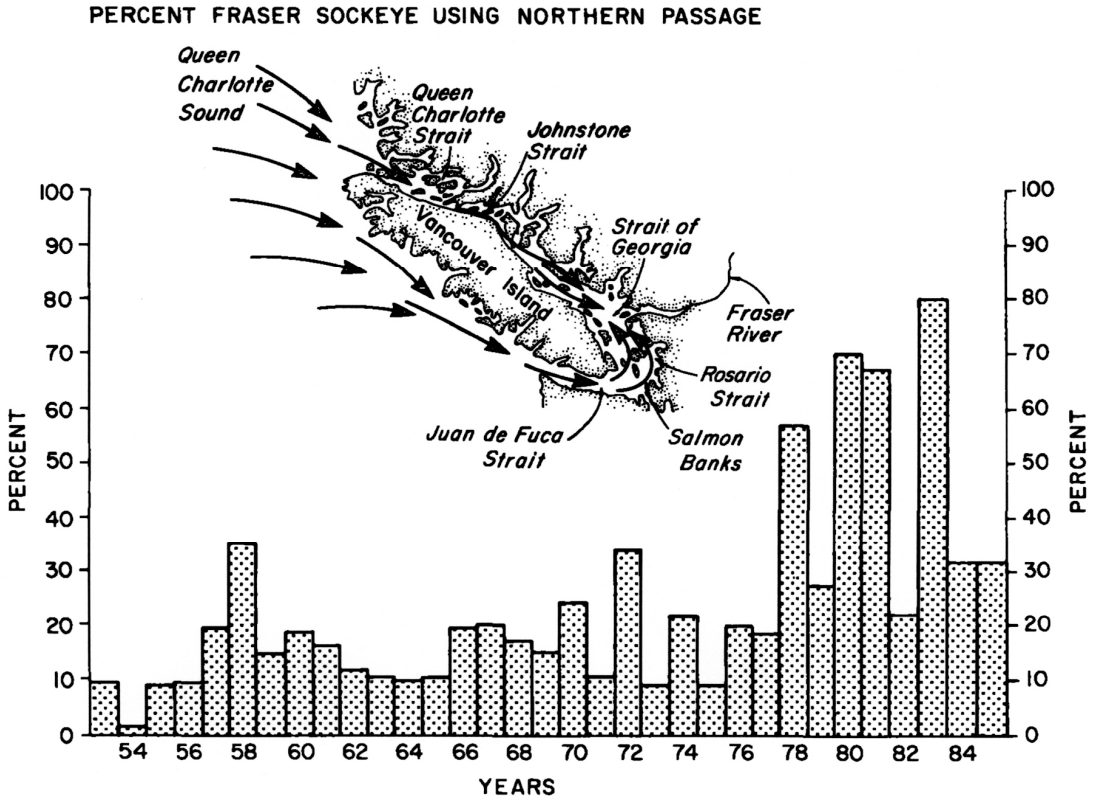

Figure 46: Percentage of Fraser River sockeye salmon taking the northern diversion from 1953–1985. Figure taken from Groot and Quinn[37].

The reason for migrating via one route versus the other is currently unknown, but higher northern diversion rates are generally associated with a warmer coastal ocean[125, 129, 37]. The relationship between northern diversion and coastal SST was not a very useful predictor of the northern diversion rate before 1978, except perhaps in those few years of greatest positive temperature anomalies[38].

Likewise, the location where Fraser River sockeye salmon make their "decision" to migrate around Vancouver Island is not known. From high seas tagging studies, those individuals that were tagged in the Gulf of Alaska in spring west of 130°W longitude (to exclude fish that were tagged along the west coast of Vancouver Island) and recovered in the same year in fisheries in one of the two the approach routes to the Strait of Georgia (Johnstone Strait and Juan de Fuca Strait) had no significant difference in the mean tagging location in the Gulf of Alaska (Figure 47). The "centre of gravity" of the fish taking the Johnstone Strait route, for example, was no farther north and/or west than the fish taking the Juan de Fuca Strait route. Although this result was obtained from a composite of all release years, it suggests that the route taken around Vancouver Island by these sockeye salmon in the 1960s and 1970s was determined closer to the coast. There were insufficient recoveries in the approach routes to know whether this pattern holds within each year, or whether it still holds today.

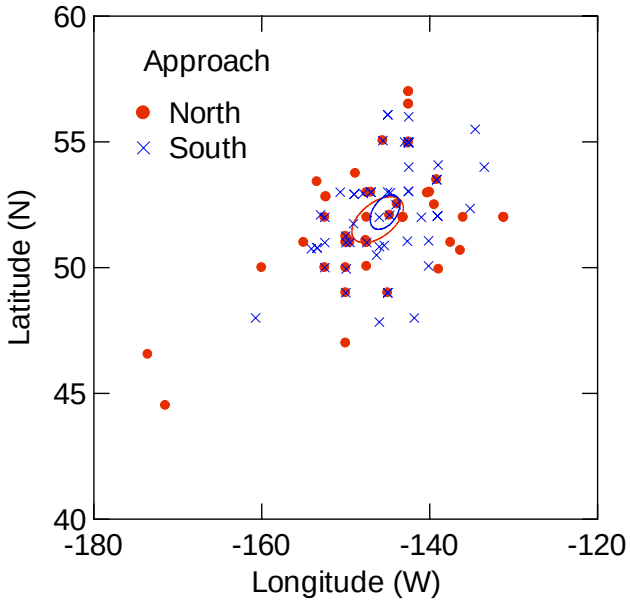

Figure 47: Release locations of age 1.2 Fraser River sockeye salmon tagged on the high seas (west of 130°W) and caught the same year in the approach routes to the Strait of Georgia, by route, composite of all recoveries.

5 Survival

5.1 Productivity and Survival

The theoretical maximum abundance that a cohort of sockeye salmon can have is determined by the number of fertilized eggs produced by its parents. The abundance of the cohort begins to decline immediately as eggs are eaten or damaged or die from any number of causes (Figure 48). The expected schedule for the eventual disappearance of a cohort is called a life table. It documents the average probability of dying during various intervals between birth and the maximum age that the species can achieve. Births and deaths of human populations, for example, are so well documented that the probabilities of dying at any particular age are relatively well known.

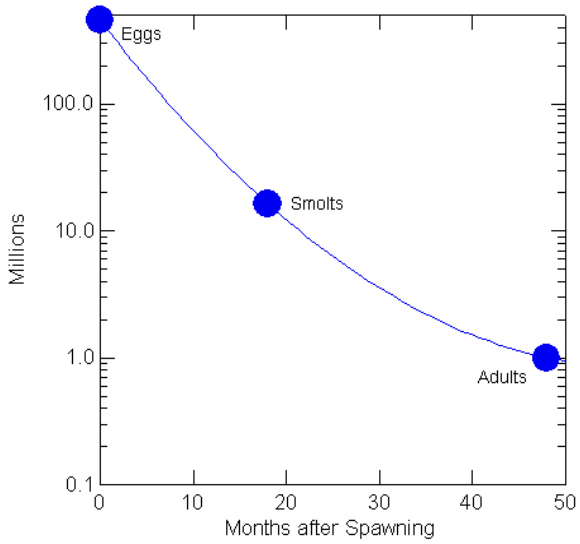

Figure 48: Abundance of an idealized sockeye salmon cohort, approximated from Chilko Lake statistics of average numbers of female spawners, fecundity, freshwater survival, and smolt-to-adult survival. Minor ecotypes (e.g., age-2.x smolts, jacks, 5- and 6-year old adults) are not shown. Note that abundance is plotted on a logarithmic scale.

> *"...it is evident that if we had some accurate method of determining from year to year the number of fish on the spawning grounds, this would afford data for prophecy"*
>
> Charles H. Gilbert, 1923

When Gilbert made the comment above, he was under contract to the Province of British Columbia to report on the returns of sockeye salmon to the major rivers of B.C. He was the professor of zoology at Stanford University from its inception. He was arguably the most influential Pacific salmon biologist during the first quarter of the 20th century, and perhaps not coincidentally, a colleague and friend of

J. Pease Babcock, Deputy Commissioner of Fisheries for B.C. One can imagine that Gilbert's wishes for spawning ground censuses reflected the aspirations of salmon population biologists of the time. The key to building a life table is the census of population abundance. As late as the 1940s, salmon escapement was referred to as "seeding" and records of abundance were ordinal[130] but by the 1950s, the estimates became more quantitative.

5.2 Difficulties Estimating Salmon Abundance

The abundance of a salmon cohort is rarely taken by census. More often, it is the sum of an *estimate* of spawner abundance in a stream or lake plus an *estimate* of the catches of that population in the fisheries it encounters on its return migration. The reliability of the estimate of spawner abundance is a determined by many factors but the counting fence has traditionally been considered to be the most reliable because an attempt is made to account for every individual migrating past a fixed point in the spawning migration. In the majority of cases, population abundance is estimated by stream walks, tagging and recapturing spawners, or some other method that relies on assumptions and inferences of varying reliability to produce an estimated of abundance.

The difficulties are relatively well known. One of the best documented examples of underestimating sockeye salmon abundance comes from the Babine River, part of the Skeena River drainage. The installation of a counting fence on the Babine River by the Fisheries Research Board of Canada in 1946 demonstrated that the estimate of abundance of sockeye salmon spawners, determined by walking streams and counting fish, was less than 50% of the total number reported migrating past the Babine River fence in the years 1946 and 1947, despite a conscientious effort of stream surveys.

> "*That stream counts will be minimal is apparent by their very nature, but the discrepancy [at Babine Lake] is beyond such expectations*"
>
> J. Roly Brett, 1952

Even an accurate census of spawner abundance each year allows only one element of a life table to be approximated: *total survival.* This is the proportion of a cohort surviving from hatching to maturity and spawning. But even this calculation requires an assumption about the average number of eggs that was fertilized by the spawning adults. That number varies from year to year and stock to stock, and from the age composition of the spawners (older females are usually larger and have more eggs). As a consequence, analysts typically avoid computing the initial size of a cohort from the number of fertilized eggs, but use instead the number of spawners (or number of female spawners) and assume that it will be a good index of the number of progeny. Compared to other sources of measurement error, this is likely a relatively small contributor.

5.3 Smolt-to-Adult Survival

One consequence of determining only *total survival* is that when the average survival changes, it is very difficult to determine where the change occurred. As Fraser River sockeye salmon spend their lives divided almost equally between freshwater and saltwater habitats, scientists who are interested in distinguishing how salmon survive in these two or more environments must take a census of the population as it leaves freshwater. Ideally this would occur immediately upstream of an estuary but the mixing of many populations from many nursery lakes within the watershed, and an inability (historically) to identify them to population of origin in a mixture, has made it easier to census sockeye salmon populations as they leave the nursery lake. Mortality of sockeye salmon between the nursery lake and the estuary is normally included in marine mortality although it is understood that some mortality occurs in the river[13].

Ricker[131] described how marine survival of sockeye salmon generally increased from 4% to 30% as the mean size of the smolts increased from 70 to 140 mm, but then he pointed out that the mean size of Chilko Lake sockeye salmon smolts varies little from year to year and with no apparent relation to average size[13], a situation that continues to the present. The first comprehensive study of smolt-to-adult survival patterns in sockeye salmon was conducted using data that had been produced by a long history of study at Cultus Lake[132]. From the 1927 to 1944 ocean entry years, smolt-to-adult survival varied from a low of 0.31% (1941) to a high of 5.78% (1936). Here, there was a significant positive relation between smolt size (both weight and length were measured) and survival, and Foerster[132] described how 56% of the variation in adult returns was explained by the number of smolts emigrating and their average weight. Ricker's[133] review of growth and survival in saltwater has not been surpassed by any other work on the topic. The average of several methods of estimating natural mortality of Pacific salmon at sea, that were thought by Ricker[133] to be without bias and had small or moderate sampling errors, in the last year at sea was 0.015 m^{-1} or 18% y^{-1}.

One pattern that the smolt-to-adult survival time series in Cultus Lake shares with its mid-Fraser neighbour, Chilko Lake, since the 1950s is that the worst survival occurred at the highest smolt abundance. Both lakes feature an underlying pattern of increasing returns from increasing numbers of smolts until a dramatic decline occurs. In Chilko Lake, all of the major deviations from this pattern are strongly negative at the highest smolt abundances. However, with only one year to make this point (Figure 49), it is not possible to know whether or not this is a general characteristic of the Cultus Lake population. In both cases, density-dependent survival is suggested. It is a general pattern, observed in nature, where the capacity of nature to support an abundance of animals is limited by some or several resource limitations.

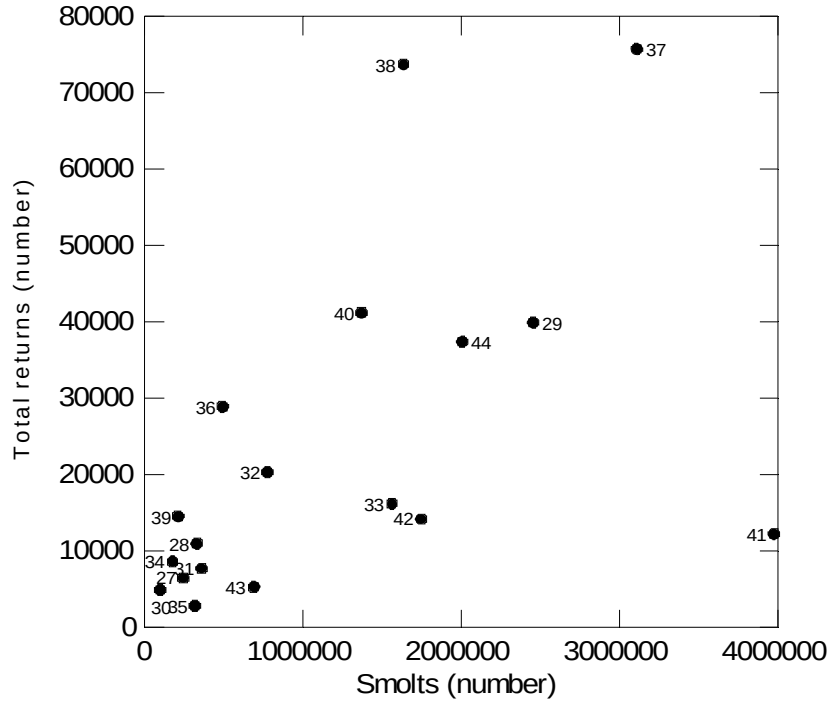

Figure 49: Adult returns of sockeye salmon (ordinate) from the abundance of smolts of the same cohort (abscissa) at Cultus Lake, 1927 to1944 ocean entry years.

The 1941 (ocean entry year) outlier was also the year of smallest mean size of smolts emigrating from Cultus Lake. It has been shown that smaller sockeye salmon smolts from Chilko Lake have greater mortality than larger individuals when a single cohort is examined[134] but the principle does not apply to differences in mean smolt size among years in Chilko Lake. In Cultus Lake, however, there was a significant relationship between mean smolt size and smolt-to-adult survival during the years from 1927 to 1944. Years with smaller average smolt size have poorer smolt-to-adult survival. The 1941 anomaly in smolt-to-adult survival did not appear so unusual when considered within this framework. Why Chilko Lake and Cultus Lake should differ so clearly on this point is not known, other than to note that Chilko Lake is the most productive sockeye salmon population, on average, and Cultus Lake is the least productive of the Fraser River populations[135]. Perhaps there are significant differences between the two populations in the energy density of smolts of equivalent size.

On average, 96% of the smolts leaving Chilko Lake are age-1.x and the remainder are age-2.x. Therefore, postsmolts of a single cohort can experience very different environmental conditions upon entering the sea. As a consequence, the marine survival of age-1.x smolts leaving Chilko Lake in any year is more similar to the marine survival of age-2.x smolts of the previous cohort than to the survival experienced by their siblings which leave one year later (Figure 50). The correlation of the former is 0.45 ($P < 0.01$), whereas there is no correlation of the latter ($P > 0.05$). However, despite sharing a common ocean entry year and location, the amount of interannual variation in marine survival shared by the two groups entering the sea in the same spring is weak ($R^2 = 20\%$), and this drops to 16% if the

calculation is made using only 44 years of data that exclude the two anomalous survivals in 1952 and 1954 at the earliest part of the time series. Without the two early outliers, the mean survival of age-2.x smolts across all other years was 12% and the mean survival of age-1.x smolts was 9% for calculations up to and including the 2004 brood year. Some of the poor correlation between groups that enter the sea in the same year may be due to inadequate biological sampling of age-2.x groups in the catch or on the spawning grounds. Because they are relatively rare, an inadequate sample of the adult returns can affect the survival estimates.

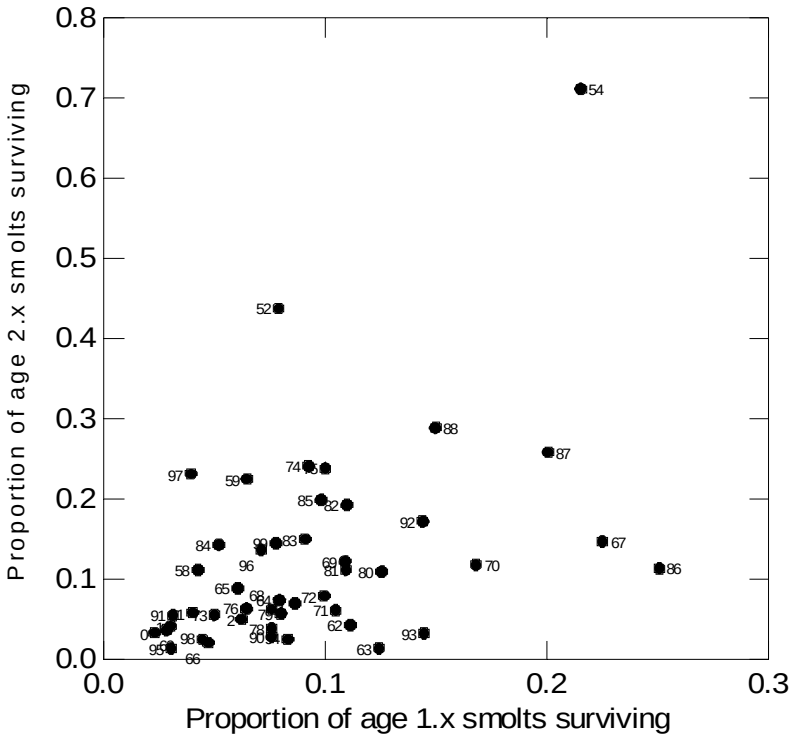

Figure 50: Smolt-to-adult survival (√ transformed) of Chilko Lake sockeye salmon of different brood years but the same ocean entry year.

5.4 Variability at Different Temporal Frequencies

The statistics of Fraser River sockeye salmon population biology are, for the most part, summarized as annual values. The degree to which finer scale within-year statistics can be computed depends on the frequency of observation. Repeated measurements of the same features using the same, or very similar, methods lead to the establishment of time series of the annual characteristics of salmon biology. Statistics that appear to vary randomly from year to year are described as having interannual variation. Should a time series of seasonal observations have a trend or cycle, or some other longer term pattern, variations of these kinds are often referred to as decadal-scale or even multi-decadal frequencies. A common approach in trying to understand the cause of variation in salmon biology is to see what

other physical, chemical, or biological time series share the same pattern of variation. The physical effects of some cycles, such as the annual cycle of warming and cooling at higher latitudes, are well known so their effects on a time series is often removed to reveal the variation that is not related to the seasonal cycle of the Sun.

The scale of an effect can be an important clue to its origin. The cause of variation in a time series that has no apparent relation to environmental variation of other nearby measurements might arise from a local effect, whereas a pattern of variation in a time series that is shared regionally may have a regional origin. A technique used to study variation in time series is to understand the spatial scale of variation as a clue to its source. Time series that are a result of multiple influences present even greater challenges, particularly when the observations themselves are imprecise or biased by the methods used to make the original observations. The latter, if an important characteristic of a time series, means that weak sources of variation will be difficult to detect.

5.4.1 Interannual

The coefficient of variation (magnitude of variability in a time series in relation to its mean value) in the number of smolts produced per effective female spawner in Chilko Lake is 47%. The coefficient of variation of age-1.x adult returns per age-1.x smolt is 60%. The coefficient of variation of total returns per effective spawner in Chilko Lake is 96%. The latter is larger because it includes variation from both sources. The important result of this comparison is that returns per spawner, the normal measure of Fraser River sockeye salmon productivity, includes significant year to year variability from both freshwater and ocean sources. Because it has not been measured routinely at other lakes, the relative influence of each habitat on total survival cannot be determined. Returns per spawner is the measurement of choice (or default) for most Fraser River sockeye salmon populations because only adults are observed in every population.

For comparison, smolt-to-adult survival of age-1.x sockeye salmon from Babine Lake (Skeena River) had a coefficient of variation of 70% for brood years 1961 to 1977[136]. This study evaluated four major assumptions surrounding the construction of spawning channels to increase adult sockeye salmon production. Assumptions about freshwater production were largely met, i.e. more spawning habitat created by the channels provided for more eggs to survive, and this translated into more fry in the lake and more smolts emigrating to sea. Only during odd years did greater numbers of adults return from the increased numbers of smolts. There was no average increase in adult returns during even brood years[136]. The difference between odd/even brood year marine survival in Babine Lake is not apparent in more recent data (brood years 1970–2000). There is no significant difference between odd and even brood year smolt-to-adult survival in Chilko Lake sockeye salmon (1-way ANOVA, $P > 0.9$) over the period of record, but a more thorough analysis of this topic is warranted in the future because of its appearance in other species using the Strait of Georgia[116].

5.4.2 Decadal

Significant changes occurred in the North Pacific ocean–climate system around 1977[137] and around 1989[138], so these years are often used to delimit climate and productivity regimes. The local expressions of these phenomena vary around the North Pacific. Spring and summer SSTs at Kains Island on the Northwest coast of Vancouver Island, e.g., they were significantly warmer (by 0.8°C) in August after 1989. In studies of Fraser River sockeye salmon productivity and climate, Beamish et al.[139, 50] found a statistically significant change (increase) in Fraser River sockeye salmon productivity following the 1976/77 climate regime shift in a subset of the time series. However, using the entire period of record and a different analytical approach, no statistically significant change in total survival was found up to the 1999 brood year[135]. In Chilko Lake, where freshwater and postsmolt survival can be distinguished, he found that average freshwater survival had declined after 1989 (up to the 1999 brood year) but he found no statistical evidence of a significant decline in average postsmolt survival during the same period. This result was likely due to having few complete years of data after the decline in survival, and by not recognizing 1992 as the year of when the change occurred. However, by extending the time series to the 2004 brood year, using 1992 as the ocean entry year of change in mean survival (√ transformed), a significant decrease ($P < 0.05$) was found for both smolt ages. The difference in average freshwater survival seems to have disappeared because of recent, unexplained high freshwater survival of the 2005 and 2006 brood years in Chilko Lake.

5.4.3 Evolutionary-scale

Selective pressures in the environment affect the evolution of heritable characteristics of sockeye salmon populations. Populations that are found in the Fraser River have evolved to their contemporary diversity over millennia, since the start of the retreat of the Laurentide ice sheet from the coastal region approximately 10,000 years ago. Hodson[140] concluded that variation in migratory timing among sockeye salmon populations was related to spawning time, migration distance, river temperature and flow regimes. She found that long delays between migration and spawning occurred in coastal areas, some of which had warm freshwater temperatures during the migration. She suggested that long delays provided the means to avoid higher temperatures which occur after migration in freshwater. For some populations, it was unclear why they should return early, with a long delay before spawning, rather than return on a date that would provide a shorter delay before spawning, after freshwater temperatures had declined from their peak.

An alternative (and at this point, speculative) idea that has not been considered previously, entertains the possibility that migration timing in sockeye salmon at the southern end of the species range has evolved to the present state by selective forces operating in the ocean, enroute to freshwater. It has the following logic:

1. Some populations of sockeye salmon, especially near their southern ocean entry locations, migrate from saltwater to freshwater far sooner than is expected from time of spawning.
2. Populations that exhibit the most extreme form of this type of behaviour have a shared geography in the northern California Current region.
3. The northern California Current region is subject to large interannual variations in physics, chemistry, and biology because of its proximity to the North Pacific Transition Zone between the Subarctic and the Subtropic.
4. The migration timing anomalies occur with diminishing frequency northward.

5. Fraser River sockeye salmon do not exhibit this behaviour because the Johnstone Strait approach route provides relief from the evolutionary forces that affect West coast populations.
6. High northern diversion rates in warm years are the interannual response to oceanic selective pressure.
7. Migration timing is a highly heritable characteristic and early arrival occurs in affected populations because evolution has extinguished later arrivals suggesting that the ocean is unsuitable for sockeye salmon migration when they might otherwise (based on spawn timing) appear in freshwater.
8. A seasonal northward expansion of the Subtropical/Transition Zone region is the cause; for reasons that keep sockeye salmon from this region on the high seas.
9. A less drastic result of this pressure is the role of the ocean in determining a high northern diversion.
10. Any expansion of the inhospitable region will provide greater selective pressures to avoid it.

5.5 Tag Recapture Rates as a Proxy for Survival

It is not uncommon to attempt to estimate marine survival of salmon using the percentage of tags recaptured. Where the fishing effort is high and the probability of detection is high, the result can be a good approximation, if not an absolute estimate, of marine survival. Coded wire tags have been used routinely to understand the migration and survival of coho salmon and chinook salmon[141, 142, 143]. From 1964 to 1968, sockeye salmon postsmolts, potentially of any population, were tagged and released throughout coastal North Pacific Ocean, including the Bering Sea[35]. A total of 40, or 0.4% of the 9,883 tagged in these years was subsequently recovered after two or three years at sea.

Of the 40 recoveries of tagged age-x.0 sockeye salmon that have ever been recovered, six (14.6%) were taken in one seine set on the coast of Southeast Alaska on July 24, 1968. Hartt and Dell[35] did not report the numbers caught on that specific day, but they made only four sets during a 10-day period, with a total of 59 sockeye salmon caught in the four sets. If all 59 sockeye were taken in only one of these four sets, the minimum survival rate from that one set would have been approximately 10%. If each of the four sets caught ¼ of the 59 fish, the survival rate from the set with the tagged fish would be approximately 68%. Each of these six tagged sockeye salmon was recovered in fisheries along the B.C. coast in 1970.

In general, however, the tag recapture rates measured in the seine operations from 1964 to 1968 were remarkably low, considering that the average smolt-to-adult survival for Chilko Lake sockeye salmon during brood years that correspond to these tagging years (~1961–1966) was approximately 8.5%. Why should the probability of survival of sockeye salmon tagged at sea at a later stage of life be more than an order of magnitude lower than the probability of survival of fish just leaving Chilko Lake? On average, it cannot be lower, so the results suggest either heavy mortality from tagging or a remarkably low probability of tag detection, or a combination of both. It suggests that reliable measures of survival will not be found in the existing high seas tagging data.

5.6 Leading Indicators of Survival

In generating the 2009 forecast, long-term average productivities had been assumed, which seemed reasonable given that marine indicators suggested that conditions for salmon going to sea in 2007 would be relatively good.

Crawford and Irvine, 2010

5.6.1 Comparisons with coho salmon survival

Most Fraser River sockeye salmon and most coho salmon rear in freshwater for one year before migrating to sea[144]. The value of observing variations in the survival of coho salmon, for a study of sockeye salmon, is their habit of returning to spawn one year earlier than sockeye salmon of the same brood year. A large fraction of the year-to-year variation in marine survival of coho salmon is shared commonly with other coho stocks along the North American continent suggesting that a large-scale factor (or factors) is affecting all[143]. While the two species have different behaviours upon reaching the ocean, there is a potential for oceanic anomalies to affect both species, where they share a common environment. Indeed, this was the case for the 2003 brood year when both species entered a coastal ocean in 2005 which was not very hospitable for some salmonids[145, 146].

Some experimental forecasts are beginning to consider how variation in the coastal oceanic environment affects salmon survival. Trudel et al.[147], for example, described how low coho postsmolt growth is associated with poor coho marine survival. For the 2005 brood year (2007 ocean entry year), marine survival varied markedly among populations (Figure 51). For the Strait of Georgia populations, marine survival of the 2005 brood year was low but not the worst ever observed; that accolade belongs to the 2003 brood year. Marine survival of the 2005 brood year of Carnation Creek coho salmon near Barkley Sound was remarkably high, but this is (currently) a small run of coho salmon with few spawners where small changes in numbers can generate large changes in survival percentage. Marine survival of the larger Robertson Creek coho salmon population for the 2005 brood year was near the long-term average.

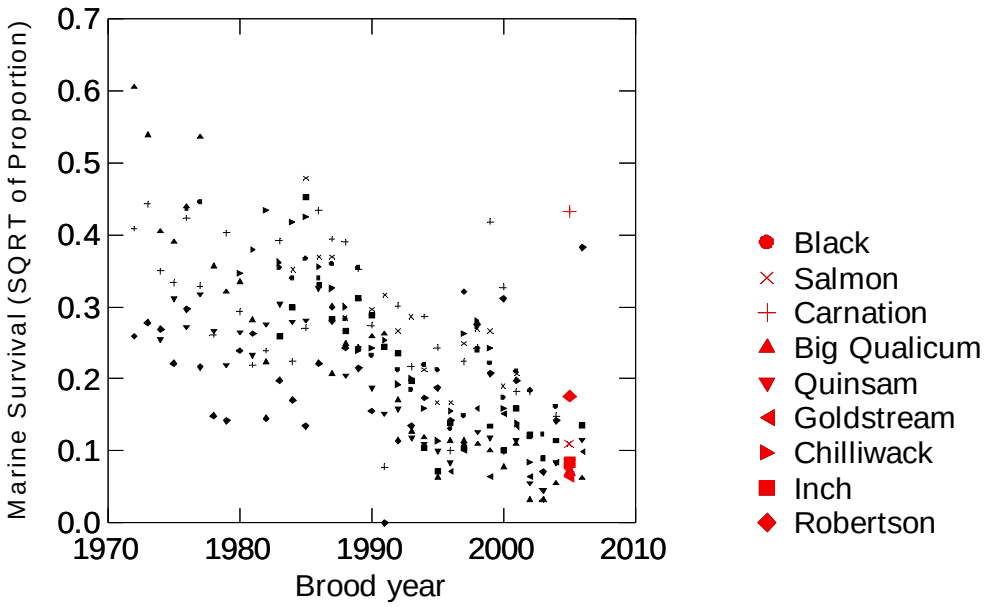

Figure 51: Marine survival (√ transformed to emphasize variation at low survival) versus brood year for seven hatcheries in the Strait of Georgia and two (Robertson and Carnation) on the West coast of Vancouver Island. Marine survivals for the 2005 brood year (2007 ocean entry year) are highlighted in red.

Forecasts of survival and returns of Fraser River sockeye salmon have been made on the basis of the Strait of Georgia surveys by DFO but forecast performance has been highly variable during the short period it has been attempted. As the focus of sampling in the Strait of Georgia is coho and chinook salmon survival, its summer and fall sampling schedule captures only a fraction (probably variable from year to year) of the April–July migration of Fraser River sockeye salmon postsmolts from the Strait of Georgia. Nevertheless, these data were used to predict the returns of Fraser River sockeye salmon beginning in 2007[148]. The first forecast in 2007 was for above average marine survival and above average returns, based largely on the observation that the sockeye salmon postsmolts caught that year in the Strait of Georgia were larger than in previous years. Returns in 2007 were among the lowest observed, with the lowest marine survival ever recorded to that point in history. Likewise, sockeye salmon returns to the Fraser River in 2008, based on the Strait of Georgia sampling in 2006, were expected to provide above average returns. Returns in 2008 were below average, with no fishery permitted. The forecasts of Fraser River sockeye salmon returns in 2009, based on sampling in 2007, were expected to be extremely poor, and this was what occurred.

5.6.2 Preliminary signs of 2010 abundance[xi]

Gillnet test fisheries in the approach routes to the Fraser River are augmented each year by purse seine test fisheries as the abundance of the annual return builds. They provide data on the abundance of maturing age 1.1 sockeye salmon (jacks) that the gillnet test fisheries miss. Jacks sockeye salmon spend only one year at sea before maturing and therefore are too small to be caught by the mesh size of commercial gillnets. Although they represent only a small fraction of the population each year, the value of jack abundance information, if a representative sample can be obtained, is a one year look ahead at the magnitude of the cohort that will return the following year (assuming relatively constant age at maturity).

From 2000 to 2009, Fraser River sockeye salmon jacks in the Blinkhorn Island test fishery (upper Queen Charlotte Strait) are about twice as abundant as in the San Juan purse seine test fishery. Nevertheless, there is an highly significant positive correlation ($r = 0.97$, $P < 0.001$) between the aggregate annual CPUE of sockeye salmon jacks caught in the Blinkhorn Island purse seine test fishery and the same in the San Juan purse seine test fishery (Figure 52). Although the magnitude of the correlation is heavily influenced by the high catches of jacks of the 2006 brood year, i.e. jacks that returned in 2009, it suggests that over the range of observations the two independent purse seine test fisheries are detecting the same jack abundance signal. The correlation for older maturing sockeye salmon is 0.64.

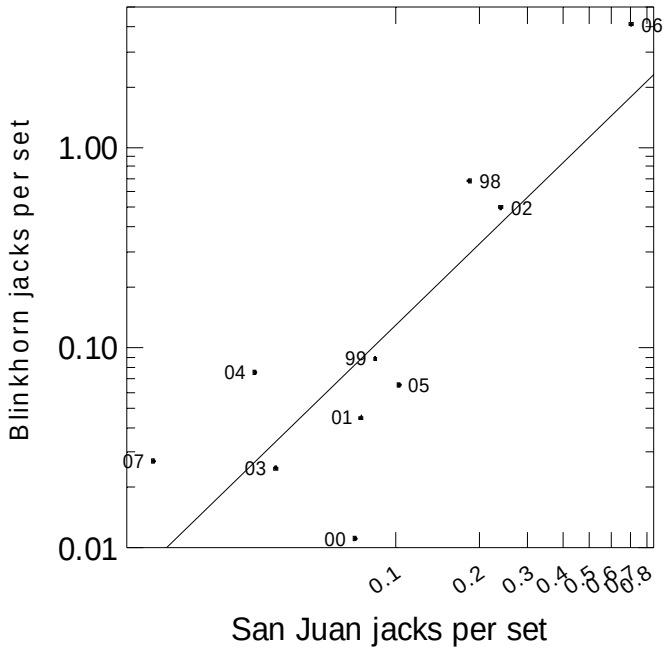

Figure 52: Comparison of Blinkhorn Island sockeye salmon jacks per set versus the same at San Juan, on log scale.

xi Summary of a presentation to the DFO Fisheries Oceanography Working Group, February 16–17, 2010.

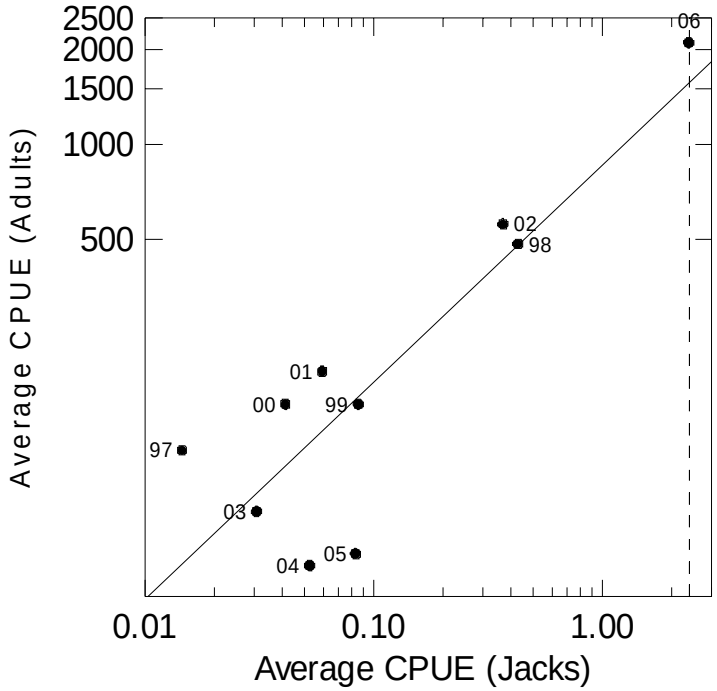

Figure 53: Average CPUE of adult sockeye salmon in the Blinkhorn Island and San Juan purse seine test fisheries versus the same measure for jack sockeye salmon, by brood year. Vertical dashed line indicates the jack CPUE measured in 2009 for the 2010 adult return. Data are presented on a logarithmic scale to emphasize variation at low CPUE.

The relationships between the average CPUE of sockeye salmon jacks in the test fisheries and the following year's CPUE of adult sockeye salmon (Figure 53) or total brood year returns (Figure 54) indicates that this measure may be useful for detecting some of the large-scale changes in abundance that have been observed from 2000 to 2010. The 2006 brood year outlier was evident in 2009, but because it was more than fivefold greater than the next highest value (1997 brood year), it was difficult to know how large the return would be. As there was no fishery in 2009, the purse seine test fisheries were one of the few sources of this information.

Sockeye salmon jack CPUE in the purse seine test fisheries does not appear to be very reliable when jack CPUE is <0.1 per set. The total return the following year can vary from 1.5 to 7 million. Most of the signal in this relationship is related to the abundance of late-run sockeye salmon (as indicated by the 4-year interval between years of high CPUE and high total returns). The relatively good return of the 1997 brood year was not detected by the jack CPUE index because the dominant populations that made up the return in 2001 do not have populations with significant numbers of jacks.

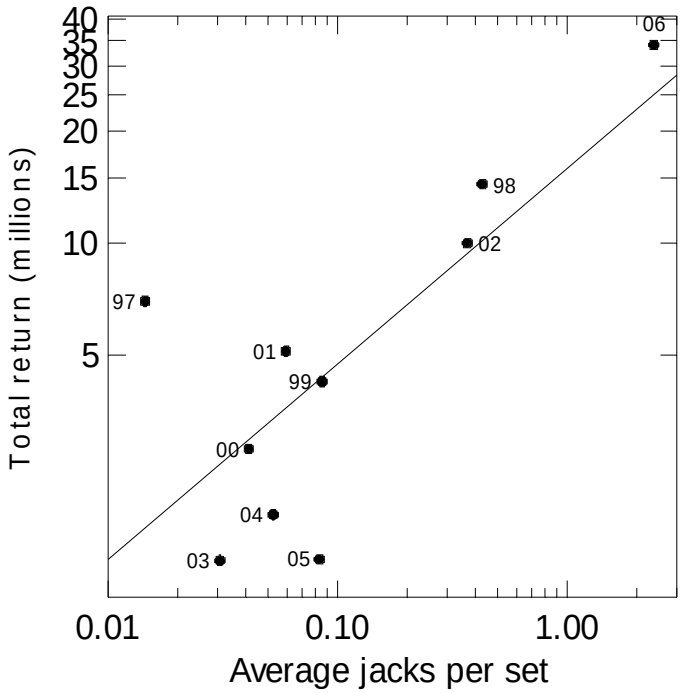

Figure 54: Total returns of Fraser River sockeye salmon versus the average numbers of jacks caught in Blinkhorn Island and San Juan purse seine test fisheries, by brood year. he 2006 brood year total return is the in-season abundance estimate from August 31, 2010 provided by the Pacific Salmon Commission.

Summary – The existence of a relationship between the abundance of age 1.1 sockeye salmon in one year and the abundance of returns of age-1.2 sockeye salmon the following year is an indication that the magnitude of the sockeye salmon return to the Fraser River was largely determined prior to the time when the age-1.1 returned. If the major cause of variation in survival occurred after the age 1.1 sockeye salmon returned, there would be little reason for them to correspond. However, because most of the signal in that relationship comes from the Late-run sockeye salmon, it is not possible to know if it applies only to this component or to the others as well. Clearly, it cannot apply to stocks that lack detectable numbers of jacks.

6 Oceanography and Climate

In the eastern North Pacific Ocean, Pacific salmon are generally found in the Subarctic region of the Gulf of Alaska, although their range in North America extends from the Arctic Ocean to southern California[149]. While southern California is not normally considered Subarctic, it has a cool and productive coastal oceanic habitat because of summer upwelling winds. They create an oceanic habitat that makes it possible for the range of Pacific salmon to extend southward to latitudes that they might not otherwise reach. The active upwelling zone is a relatively narrow band of water 10–25 km wide along the North American coast[150], implying that unsuitable oceanic water is nearby and kept at bay by suitable winds. Their failure can have rather devastating effects. The widespread mortality of juvenile Pacific salmon in 2005 was attributed to the extremely delayed seasonal upwelling winds that year. For many populations of salmon that went to sea in 2005, from Vancouver Island southward, it was the worst survival on record. The low returns of maturing Fraser River sockeye salmon in 2007 were a result of the lowest recorded survival for this river. The remainder of this section considers sequentially, the oceanic environment along the migration route from the Strait of Georgia to the open Gulf of Alaska, with special attention given to the state of the environment while the 2007 ocean entry year of Fraser River sockeye salmon was at sea.

6.1 Strait of Georgia

6.1.1 Wind

Hourly meridional (V) and zonal (U) winds (m s^{-1}) from 1967 to the present (mid-2010) at the Environment Canada station at Sandheads (49°06′21.225″ N, 123°18′12.123″ W) were rotated by 125° to provide the along-strait and cross-strait components of wind speed in the Strait of Georgia instead of N–S/W–E components that are typically reported by Environment Canada. The rotated U component is the wind speed toward 35° compass direction and the V component is the wind speed toward 305°. Relatively rare gaps in the time series were filled by developing regression equations with Entrance Island (near Gabriola Island) winds. Weekly averages of the rotated winds were calculated from the hourly values using all years of data and from these, weekly anomalies were calculated.

Apart from the first week of 2007, average weekly cross-strait winds did not deviate much from average for most of 2007 (Figure 55). Weekly average along-strait winds were more variable, with a tendency for stronger than average up-strait winds (southeasterlies) through most of the spring. Up-strait winds are the norm at Sandheads most of the year.

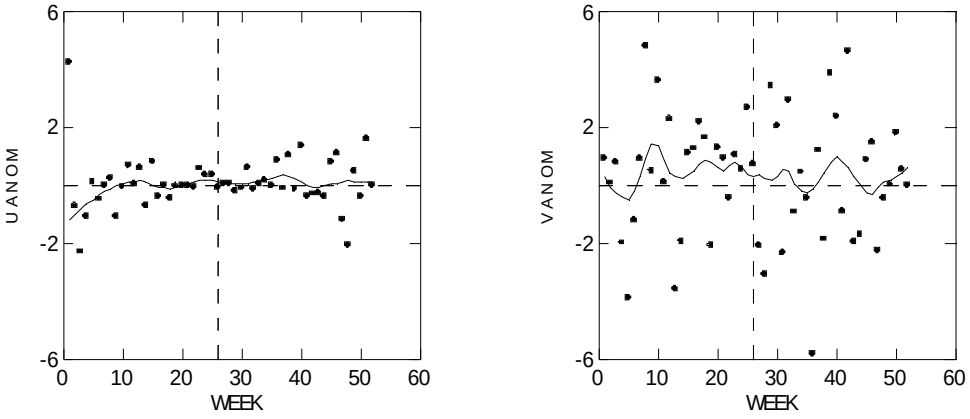

Figure 55: Weekly cross-strait (left) and along-strait (right) wind speed anomalies by week in 2007. Vertical dashed line indicates the end of June. The horizontal dashed line is the average value from 1967 to 2010. A loess smoother was used to create the trend lines. Rotated data courtesy of Susan Allen and Jeremy Sklad (UBC).

6.1.2 Fraser River discharge

The Fraser River is the single largest source of freshwater in the Strait of Georgia[151]. Most of its annual discharge comes from melting snow and this is reflected in the sharp increase in volume in spring and summer). It creates a large plume of fresh and brackish water that spreads thinly across the Strait of Georgia and is mixed with the salty water below by tides, winds, and currents (Figure 56). Estuarine flow carries most of the Fraser River discharge out Juan de Fuca Strait where it feeds the buoyancy-driven Vancouver Island Coastal Current[152]. Within the Strait of Georgia, the fresh/brackish surface layer is buoyant because it is less dense than the colder, saltier water that lies beneath it. The surface layer is warmed by radiant energy from the Sun more than the deeper layers, which reinforces the density gradient. The Fraser River also provides the surface layer of the Strait of Georgia, with nutrients of anthropogenic (agricultural runoff, sewage) and natural origins. The daily volumes of freshwater entering the Strait of Georgia from the Fraser River were often in the upper quartile in the spring of 2007 (Figure 57a) but at no time were they at extreme levels in the nearly 100 year historical record.

Figure 56: Satellite image of lower Vancouver Island and surrounding waters. Note the muddy plume of the Fraser River discharging into the Strait of Georgia.

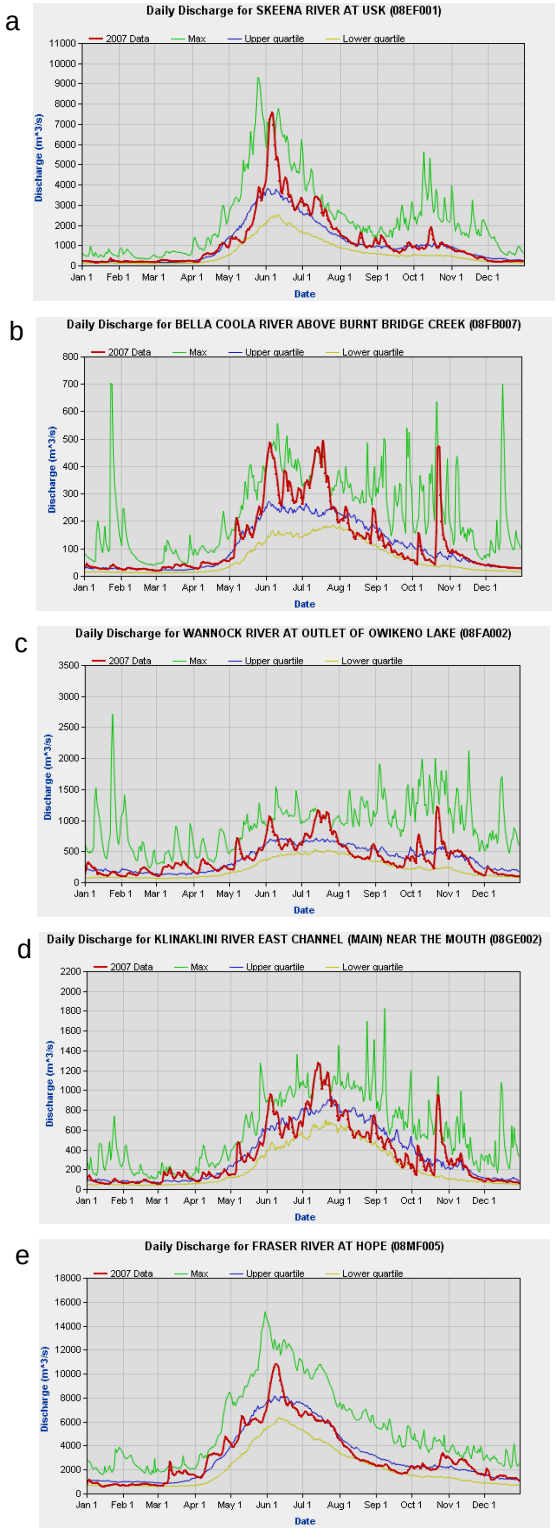

Figure 57: From North (top panel) to South, daily river discharge plots of the Skeena (a), Bella Coola (b), Wannock (c), Klinaklini (d), and Fraser (e) rivers in 2007 (red) versus maximum (green), upper quartile (blue), lower quartile (yellow). Red superimposed on green indicates maximum discharge occurred in 2007.

6.1.3 Surface water properties at lighthouses

Detailed surveys of temperature and salinity at depth in the Strait of Georgia have been conducted rather infrequently. As consequence, it is difficult to follow the history of seawater in the Strait of Georgia in any detail from scientific cruise results without interpolating/imagining the kinds of variation that may have occurred between cruises. This may change in the future with the recent development of an undersea cabled network in the Strait of Georgia.[xii] Sampling by the navy and DFO near Nanoose Bay is the only exception (see Section 6.1.4) but it is a single station that likely does not reflect the state of the Strait of Georgia as a whole. Therefore, the history of hydrographic properties in the Strait of Georgia often relies on frequently measured surface properties.

In 1934, John Tully, an oceanographer with the Fisheries Research Board of Canada, encouraged keepers at some coastal lighthouses to adopt standard practices for measuring temperature and salinity (Figure 58). Other lighthouses, including some in the Strait of Georgia joined the monitoring program in later years: Chrome Island (1961), Sisters Islets (1968), and Entrance Island (1936). The unique value of these records is that, for the most part, neither the methods nor instrumentation have changed. Having more than one measuring site provides an opportunity to understand differences and similarities around the Strait of Georgia. Furthermore, sampling at the lighthouses will likely reflect the part of the ocean that sockeye salmon experience because properties there are measured at the surface where the fish are known to migrate[39]. The record of daily observations of temperature and salinity can be downloaded from the Fisheries and Oceans Canada website[xiii]. Density was computed from these observations using a 1985 algorithm developed by UNESCO/IOC and provided by DFO.

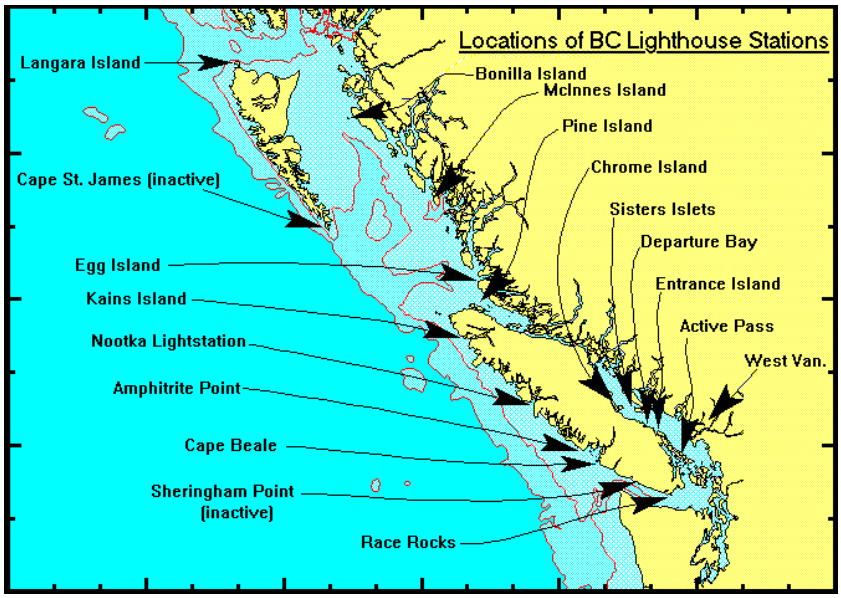

Figure 58: Ocean-climate monitoring stations along the B.C. coast. Image from Fisheries and Oceans Canada (http://www.pac.dfo-mpo.gc.ca).

xii http://www.venus.uvic.ca
xiii http://www.pac.dfo-mpo.gc.ca/science/oceans/data-donnees/lighthouses-phares/index-eng.htm

Annually averaged temperature, salinity, and density, at stations in the Strait of Georgia share a common pattern of interannual variation since 1968. Based on principal component analyses, the shared components are: SST = 92%, SSS = 86%, and density = 85%, based on measurements since 1968 (when Sisters Islets began recording data). So, it appears that if one station is warmer and fresher in any given year, so are the others. It also appears that if one station has highly variable temperature or salinity in one year, so have the others. This tendency to share averages or variances among stations is a result of physical forces (e.g., winds, tides) which tend to affect all stations similarly. The station with the densest surface seawater is Chrome Island in northwestern the Strait of Georgia and the station with the least dense surface seawater is Entrance Island, across the strait from the Fraser River. A second property of these stations is the shared relationship between the annual mean value and the annual variance. At each station there is a significant negative correlation between the mean and variance indicating that years with higher average seawater density are years with lower variability in that property.

Daily observations reveal the nature of the seasonal fluctuations in surface water properties at various locations throughout the Strait of Georgia, but they also show the ranges of these water properties (Figure 59, Figure 60, and Figure 61). To make them more comparable, the data in these figures were restricted to the period from 1968 when the Sisters Islets record began. Against this historical background of daily observations, it is possible to evaluate how the spring of 2007 (highlighted in red) compares with historical measurements. The comparison indicates that 2007 was not extreme in the historical record at any of the four the Strait of Georgia stations. Salinity and density at Departure Bay were lower than average for most of the year. Measurements at the Sisters Islets station were automated following a decision to de-staff the lighthouse in 1996/97. It did not have a full year of observations in 2007, and many high salinity and density values that year look more like instrumentation errors (Figure 60 and Figure 61). Salinities are never so high in the Strait of Georgia.

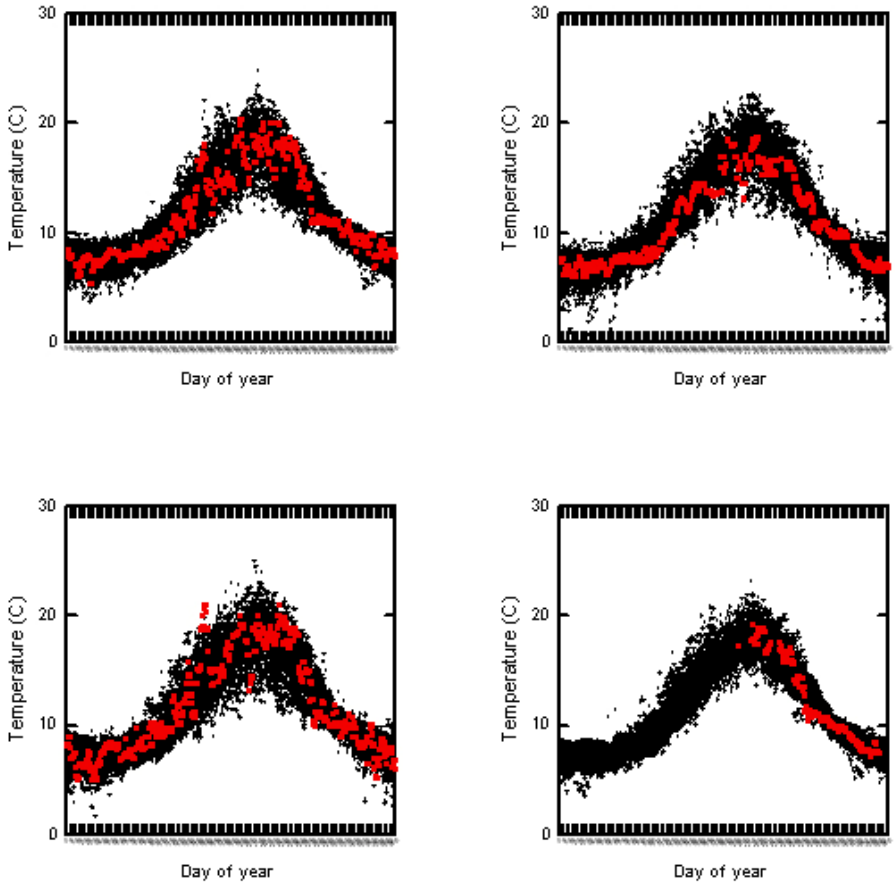

Figure 59: Daily sea surface temperatures (°C) at four stations in the Strait of Georgia (clockwise from top left: Chrome Island, Departure Bay, Sisters Islets, Entrance Island). The year 2007 is highlighted in red against all other measurements observed at that station from 1968 to 2010. Data source: Fisheries and Oceans Canada.

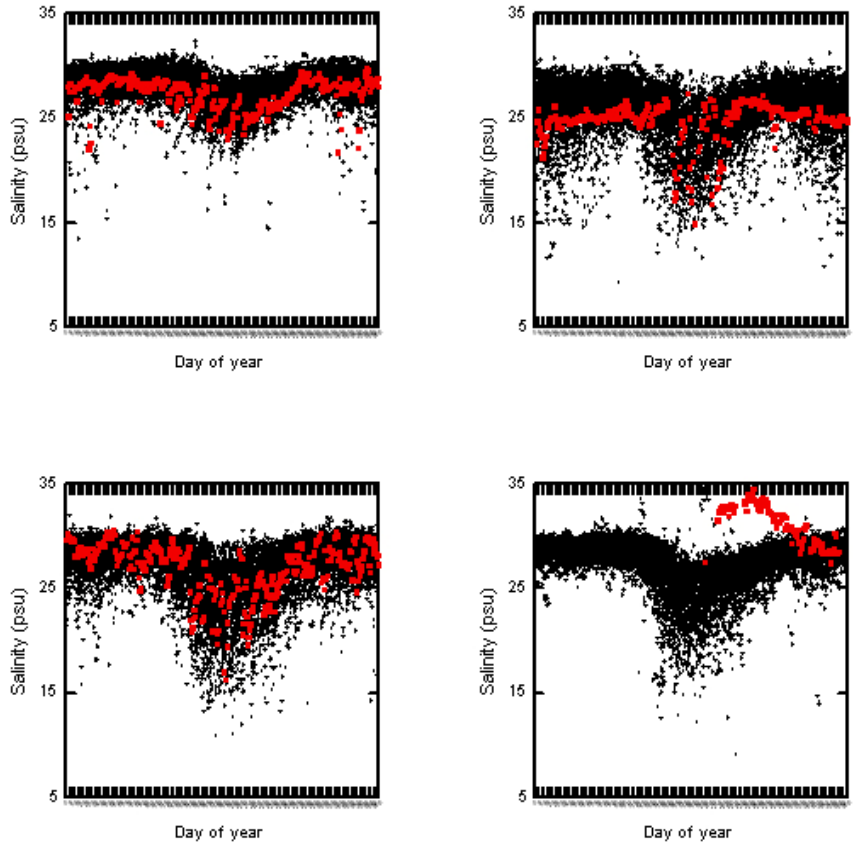

Figure 60: Daily sea surface salinities (psu) at four stations in the Strait of Georgia (clockwise from top left: Chrome Island, Departure Bay, Sisters Islets, Entrance Island). The year 2007 is highlighted in red against all other measurements from 1968 to 2010. Data source: Fisheries and Oceans Canada.

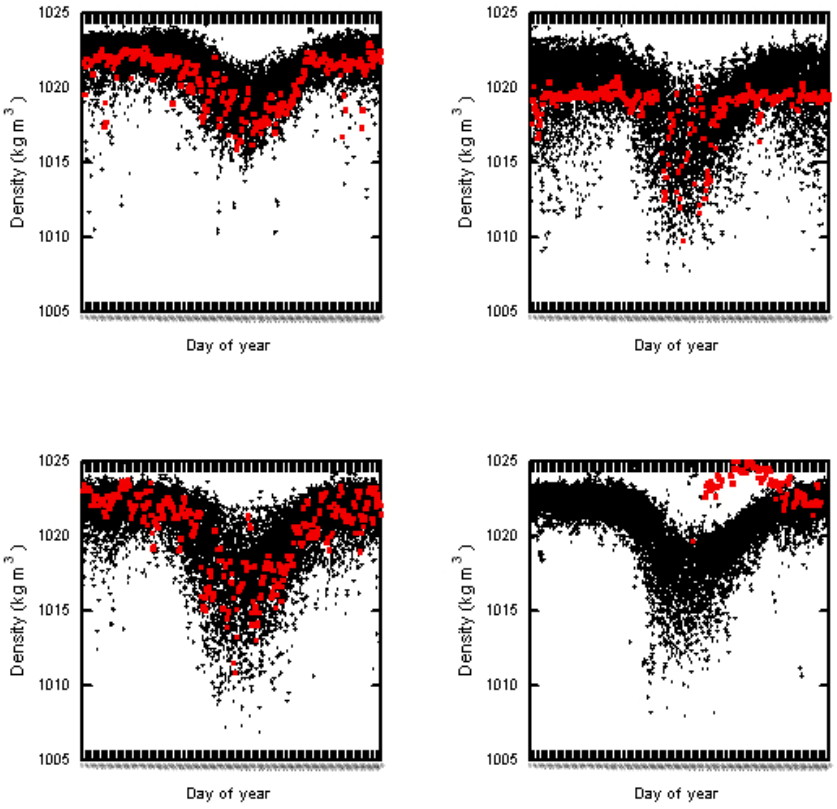

Figure 61: Daily sea surface densities (kg m^{-3}) at four stations in the Strait of Georgia (clockwise from top left: Chrome Island, Departure Bay, Sisters Islets, Entrance Island). The year 2007 is highlighted in red against all other measurements from 1968 to 2010.

6.1.4 Hydrography at the Nanoose station

The Nanoose station record of temperature, salinity, and depth extends from the late 1970s to the present (Figure 62). This station is located (49° 18.7′ N, 124° 2.7′ W) on the opposite side of the Strait of Georgia from the main migration route of Fraser River sockeye salmon and the extent to which it reflects the general hydrography of the entire strait is unknown. Cold water intrusions into the deeper waters of the Strait of Georgia occurred in the spring and early summer of 2007 following four years of relatively warmer water at depth. This inflow of deeper water from the Pacific Ocean via Juan de Fuca Strait is a normal feature of water circulation in the Strait of Georgia[153]. The 2007 intrusion returned the water column to the long-term average temperature measured over the period from 1999 to 2007[154]. The coldest intrusions in recent years occurred in 2001 and 2002 (Figure 63).

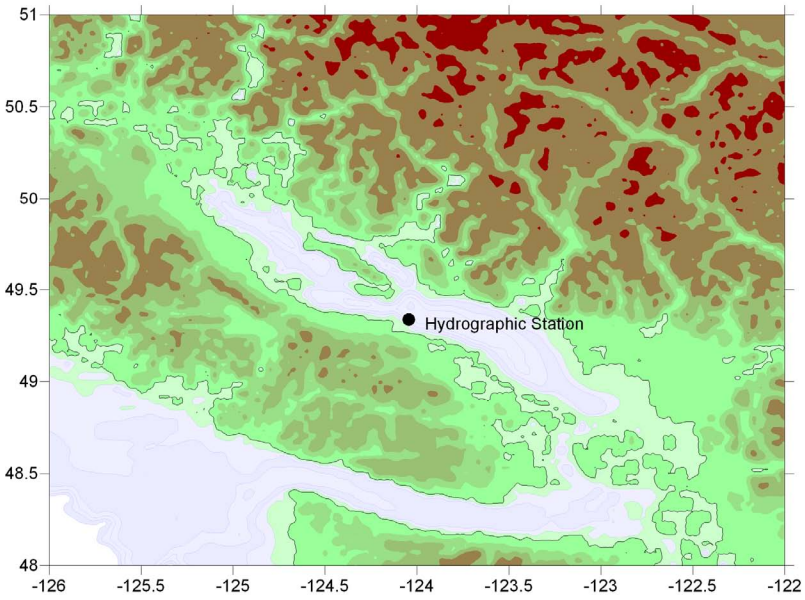

Figure 62: Location of the Nanoose hydrographic station in the Strait of Georgia.

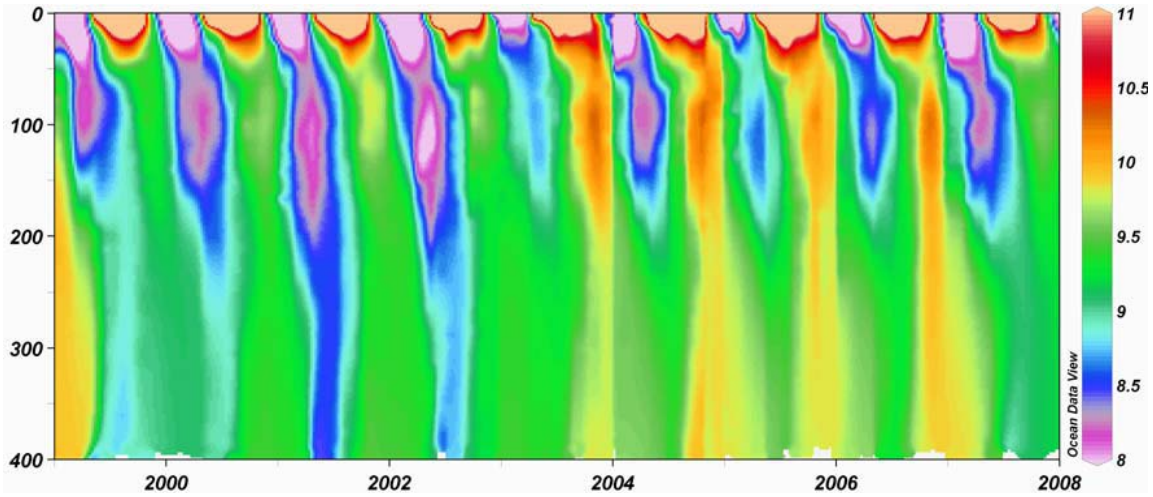

Figure 63: Smoothed temperature (°C) by depth and year measured at the Nanoose station (depth in metres) in the Strait of Georgia. Tick marks on the abscissa indicate the start of each year from 1999. Figure from Masson[154].

The Nanoose station data have been collected regularly but less often than daily so weekly average water density was computed at each depth from all casts to create a seasonal climatology at depth. For example, during the 13 week period from March 1 to May 31, 2007, 17 casts were taken. Departures from average were computed to generate a time series to indicate whether density was greater or lesser than average at each depth. An analysis of variance of the weekly density anomalies was used to determine if there were statistically significant differences among years during the period when most

sockeye salmon are migrating through the Strait of Georgia (weeks in May–June pooled). The analysis indicated that there are significant differences in water density among years in the upper water column (Figure 64). While the spring of 2007 was a strong negative anomaly (fresh) at Nanoose Bay, three other years (1994, 1996, 1997) were more extreme. A similar result was obtained if the analysis was done using only the upper 5 m instead of 10 m. What does appear in the analysis is that densities in the upper 10 m tended to be above average before 1993, and most are below average from 1993, however, considerable year-to-year variability precludes making a definitive statement about the nature of this low frequency variability in the time series.

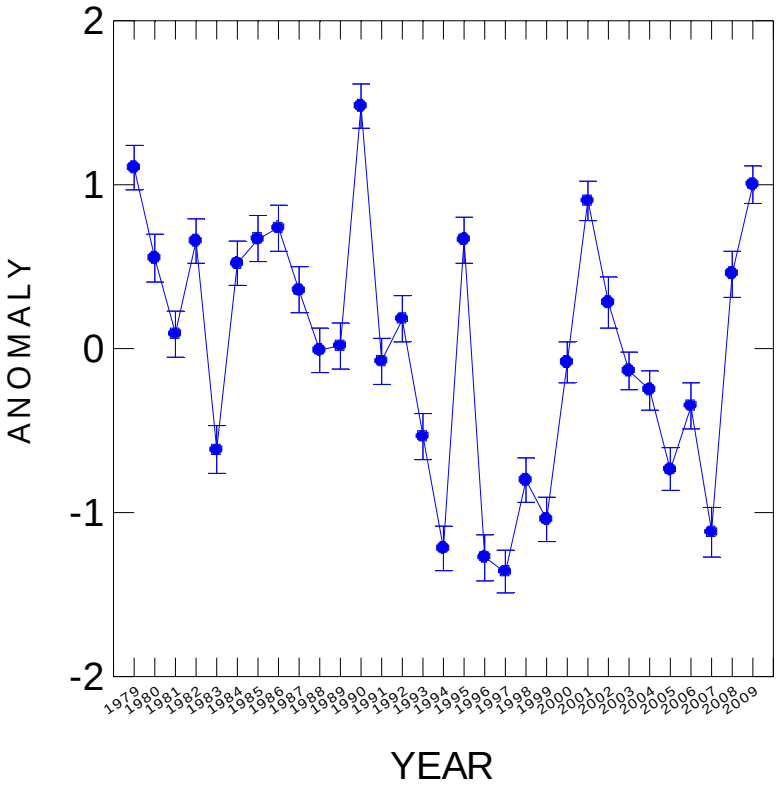

Figure 64: Average water density anomalies near Nanoose Bay in the upper 10 m of the water column from 1979 during May and June. Vertical bars indicate ±2 s.e.

While the density of the surface layer of the water column is of general interest, the greater interest is whether the gradient with depth has increased, decreased or stayed the same. If the gradient has increased over time, or in any particular year, nutrient re-supply from depth would require more work to mix them to the surface. In regions like the Subtropical North Pacific, for example, the upper layer is permanently stratified leaving the upper water column with reduced phytoplankton production[155]. A simple method of examining water column stability, based on Gargett[156] (1997), is to look at the average density difference between an upper and lower layer to determine if it has changed. Average densities were computed by week. In consideration of the relatively shallow mixed layer in the Strait of

Georgia, the difference of the average densities in the upper 5 m and the average densities in the 5–10 m layer was used as the index. As before, interannual variation in the stability index was examined by pooling the weekly results over the May/June period when most sockeye salmon are in the Strait of Georgia. This analysis indicated that seven years in the period from 1988 to 1999 tended to have higher water column stability in the upper 10 m than the period before or after (Figure 65) but the median of weekly values for the spring of 2007 is not remarkably different from the rest of the decade.

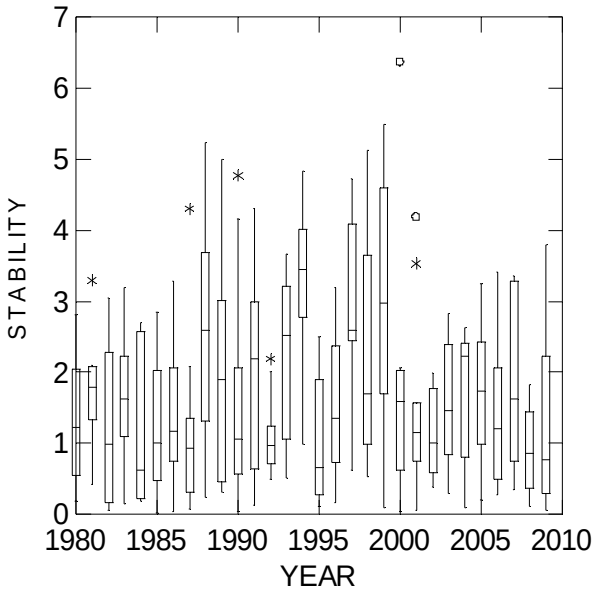

Figure 65: Box and whisker plots indicating variation in a weekly water column stability index during May and June computed at the Nanoose station by year for the months May and June, pooled. Units are σ_θ. The horizontal line at the centre of each box is the median of weekly values. The limits of the box represent the 25 and 75% quartiles.

In March, April, and May 2007, a total of 17 hydrographic casts was conducted at the Nanoose station. The depth at which the shallowest measurement was taken at each cast varied from 1–3.2 m from the surface and varied among casts. Six casts had shallowest observations at 1 m, ten casts at 2 m, and 1 cast had its shallowest measurement at 3.2 m. The average minimum observation was 1.72 m. One estimate of the average depth of the mixed layer during these months in 2007, based on salinity measurements from these 14 casts was ~1.75 m which is shallower than most of the shallowest observations during this period[157]. The very shallow average mixed layer depth for the period may have arisen because the mixed layer depth was set, arbitrarily, to zero if the algorithm failed to generate an estimate. If these zeros were included in the computation of the average, a shallow value would have been produced.

6.1.5 Nanoose as an index of water properties in the Strait of Georgia

Comparing monthly averaged surface seawater density computed from lighthouse data with that measured at the Nanoose hydrographic station since 1978 reveals a seasonal pattern of shared interannual variation between the three locations (Figure 66). Monthly-averaged near-surface (<3 m) seawater density at Nanoose Bay is most similar to monthly-averaged surface seawater density at the Chrome Island lighthouse in February. The correlation diminishes through the late winter and spring to a low in June. Monthly-averaged near-surface (<3 m) seawater density at Nanoose Bay is most similar to monthly-averaged surface seawater density at the Entrance Island lighthouse in February. As with Chrome Island, the correlation diminishes to a minimum in June. It suggests that the density of the near-surface seawater at the Nanoose station becomes least like that at two lighthouses at other locations in the Strait of Georgia in June. Whether this reflects an increased spatial heterogeneity in surface seawater density at this time of year is unknown. Correlations between the two lighthouses were highest in July. This may reflect a greater tidal influence at the lighthouses, where more intense tidal mixing over the rough bathymetry of the shoreline may tend to reduce differences that develop in less turbulent waters.

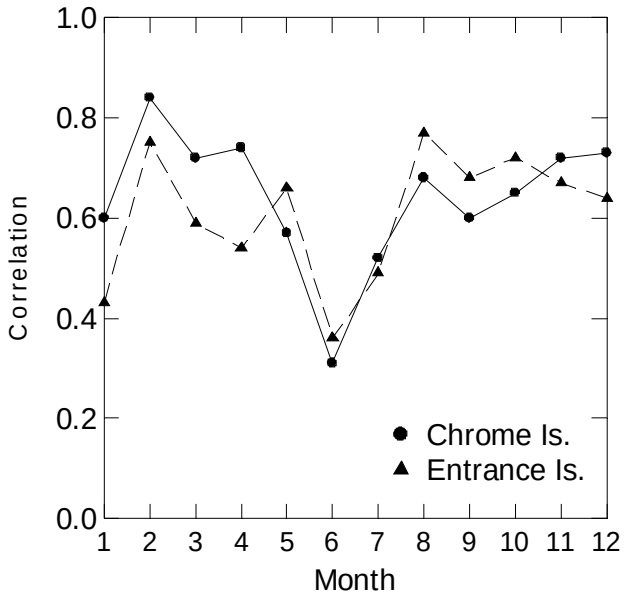

Figure 66: Month-to-month correlation between surface seawater density at the Nanoose hydrographic station and surface seawater density measured at two lighthouses in the Strait of Georgia. All are on the western side of the strait.

6.1.6 Nutrients and chlorophyll

A mid-channel transect of 20 stations through the Strait of Georgia and Juan de Fuca Strait has been sampled by DFO for *in situ* chlorophyll and nutrients since 2002. Phytoplankton and nitrate concentrations during the winter and spring of 2007 were found to be similar to what had been observed from 2002 to 2006[158]. During the summer of 2007, however, phytoplankton concentrations were higher at most of the stations. Phytoplankton species composition was determined in most of these years but 2007 was not among them. By autumn, phytoplankton concentrations were lower, and nitrate concentrations higher than in previous years.

6.1.7 Zooplankton

Samples of zooplankton have been collected annually during the Strait of Georgia/Juan de Fuca Strait spring transect since 2002, however, no zooplankton data were collected in the survey of 2007.

6.1.8 Ichthyoplankton

An ichthyoplankton community is made up of fish eggs and larval fishes which have recently hatched. Fish eggs hatch into fish larvae in time to meet the seasonal abundance of prey that appears in spring. Hence, the greatest abundance of ichthyoplankton occurs in spring. DFO had an ichthyoplankton research program in the Strait of Georgia and on the West coast of Vancouver Island in the late 1970s and early 1980s. The program ended in the early 1980s with the publication of an extensive series of data reports (e.g.[159, 160, 161, 162, 163, 164, 165]).

The University of Victoria resumed research on the larval fish (ichthyoplankton) community in the Strait of Georgia beginning in 2007. Annual surveys were designed to provide a representative overview of the ichthyoplankton community in spring. At each station, a Tucker trawl net was towed at 2 knots for 15 minutes. The samples were preserved for examination in the laboratory. From 2007 to 2010, the last week of April was sampled every year. Preliminary results indicate that the concentrations of ichthyoplankton sampled during the last week of April did not differ among years[166].

6.1.9 Temperatures in the Strait of Georgia in 2008

Deep waters of the Strait of Georgia began cooling in mid-2007 and this continued and intensified into 2008. Surface temperatures in the strait, however, remained warmer than average or average (at Chrome Island) through the sockeye salmon outmigration[167]. Sea surface temperatures at Chrome Island were not significantly different (ANOVA: $P = 0.52$) in May–June of 2007 compared to May–June of 2008.

Summary – The stability of an ocean water column (resistance to vertical mixing) is determined by the characteristics of its density-depth profile. As both temperature and salinity (and pressure) affect density, water column stability is determined by their joint influences. In the absence of other influences, higher salinity water is denser than lower salinity water, and colder water is denser than warmer water if there is no difference in salinity. A typical density profile in the Subarctic Pacific has a surface layer of uniform density overlaying a transitional layer with rapidly changing density: higher density than the surface but less dense than the deep water. If the depth of the uniform surface layer is approximately equal to the depth of the euphotic zone (depth with enough light for plankton to grow), the surface mixed layer becomes nutrient depleted by the growing plankton, and because there is no recirculation by vertical mixing from below, biological production is limited. In the Strait of Georgia, however, the surface mixed layer is relatively shallow, on the order of a few metres, and much shallower than the euphotic zone so some nutrients remain available for plankton growth beneath the mixed layer during the summer when stratification is greatest. Year-to-year variations in these physical and chemical processes are responsible for establishing the biological characteristics that sockeye salmon postmolts experience upon entering the Strait of Georgia.

Sockeye salmon smolts begin to leave the Fraser River estuary during the last two weeks of April[39] so their interaction with the Strait of Georgia waters occurs primarily in May and June, except for underyearling sockeye salmon, which tend to delay ocean entry[3, 36]. Seawater density in the upper layer (<10 m) at Nanoose Bay was clearly lower than average in the spring of 2007, when the 2009 return year was just going to sea, but several other years in the 1990s had even lower values. There are more negative density anomalies in the latter half of the time series and more positive density anomalies in the earlier half, but there is also considerable interannual variation. The years 2008 and 2009 were strongly positive density anomalies. Water column stability in the top 10 m in May and June of 2007 at Nanoose Bay was within the range of variability observed there since 1979. Year-to-year variation in water properties in the near-surface layer at the Nanoose station resembled that found at lighthouses distributed around the Strait of Georgia, but the resemblance varies seasonally. Near-surface water properties at the Nanoose station are least correlated with these other locations in the Strait of Georgia (Chrome Island and Entrance Island) in the month of June. The mid-channel transects of water properties (since 1999), nutrients, and chlorophyll (since 2002) from the northern the Strait of Georgia to the mouth of Juan de Fuca Strait revealed that 2007 was not unusual except for higher than average nutrients and chlorophyll in summer. The abundance of icthyoplankton in the Strait of Georgia in the last week of April of 2007 was no different from that found during the same week from 2008 to 2010[166]. May and June average SSTs at Chrome Island were not significantly different between 2007 and 2008.

6.2 Coastal Gulf of Alaska

6.2.1 General description[xiv; 168]

The Gulf of Alaska coastal area has a nearshore, poleward, buoyancy-driven coastal current, called the Vancouver Island Coastal Current in the south and the Alaska Coastal Current in Alaska. During the summer months, the Alaska Coastal Current has local reversals and small eddies which can concentrate plankton and small fishes in convergence zones for foraging fish, birds, and marine mammals[169].

The broad and sluggish Alaska Current (3–6 m min^{-1}) originates in the bifurcation of the North Pacific Current as it reaches the North American continent from Asia[170]. It carries variable portions of the warm North Pacific Current northward along the coasts of northern British Columbia and Southeast Alaska into the northern Gulf of Alaska[171]. The Alaska Current turns westward in the northern Gulf of Alaska, where it is separated from the low nutrient Alaska Coastal Current by a highly variable mid-shelf region. The mid-shelf region is characterized by pronounced changes in water properties, chemistry, and species compositions of phytoplankton, zooplankton, and fish along cross-shelf gradients.

Superimposed on these cross-shelf gradients is considerable mesoscale variability resulting from eddies and meanders in the boundary currents[172, 173, 174, 175]. Forced to the south by the Alaska Peninsula, the Alaska Current continues as the much swifter (18–60 m min^{-1}) Alaskan Stream as it follows a southwestward course along the Alaska Peninsula and the Aleutian archipelago[176]. A portion of the Alaskan Stream turns south and recirculates as part of the North Pacific Current, closing the loop to form the Alaska Gyre. The position of the North Pacific Current and the volume of water transported vary on interannual and decadal time scales, with associated variations in the Alaska Current[177, 171].

From South to North, lighthouses at Pine Island, Egg Island, McInnes Island, and Bonilla Island, are situated along what could be considered as the "inside" migratory path of Fraser River sockeye salmon postsmolts, while Amphitrite Point, Kains Island, and Langara Island are located on the "outside" migratory route but is landward of the shelf break on the West coasts of Vancouver Island and Haida Gwaii. The oldest of the salinity and temperature time series from these lighthouses begins in 1935.

By 2007, most of the Gulf of Alaska was significantly cooler than the peaks reached in 2005 and this was reflected in below average to average daily SSTs at many coastal lighthouses. However, in about mid-June, there was an abrupt shift to warmer water at five of six lighthouses. Only the McInnes Island lighthouse in Hecate Strait did not indicate a summer anomaly but there are indications of it at other lighthouses beyond the Strait of Georgia. The number of days that SST anomalies exceeded +2°C between mid-June to mid-September, 2007 were: Amphitrite Point (10 days), Kains Island (14 days), Egg Island (12 days), Langara Island (1 day), and Pine Island (4 days). Stations in the Strait of Georgia did not exhibit this anomaly pattern (Figure 59).

xiv Abstracted from Mundy et al.[168].

Daily salinity anomalies in 2007 tended to be fresh at most of these lighthouses, and very fresh at Egg Island in eastern Queen Charlotte Sound (Figure 60). The abrupt positive anomalies in SST that appeared at some lighthouses were not accompanied by a similarly timed pattern of salinity anomalies except at Egg Island in Queen Charlotte Sound where salinity decreased to record lows in summer and SST increased.

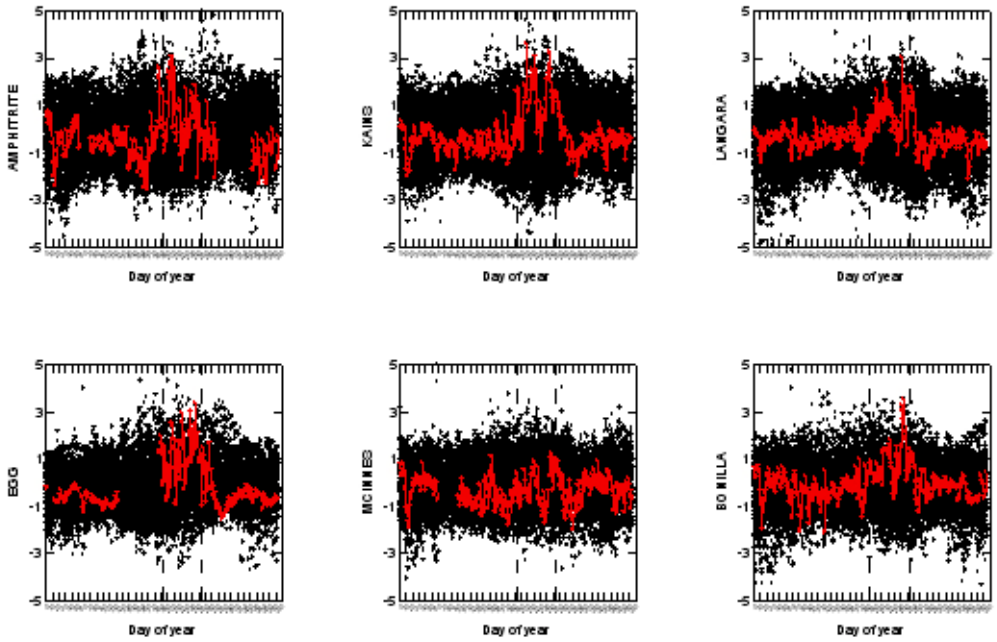

Figure 67: Daily sea surface temperature anomalies (°C) at six ocean-climate monitoring stations beyond the Strait of Georgia (Amphitrite Point, Kains Island, Langara Island, Egg Island, McInnes Island, and Bonilla Island). The year 2007 is highlighted in red against all other anomalies observed at that station. Anomalies are observed values minus average values for each day of year. Average values are computed from the range of years, 1977 to present. Vertical dashed lines indicate July 1 and August 31 when most of the Fraser River sockeye salmon postsmolts would normally have left the Strait of Georgia.

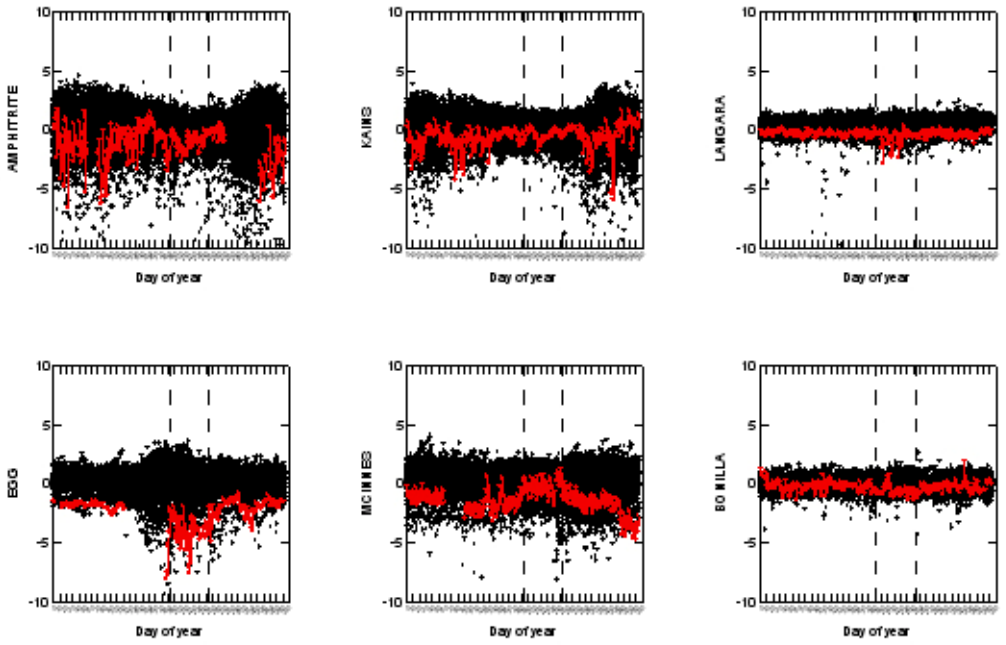

Figure 68: Daily sea surface salinity anomalies (psu) at six ocean-climate monitoring stations beyond the Strait of Georgia (Amphitrite Point, Kains Island, Langara Island, Egg Island, McInnes Island, and Bonilla Island). The year 2007 is highlighted in red against all other anomalies observed at that station. Anomalies are observed values minus average values for each day of year. Average values are computed from the range of years, 1977–2008. Vertical lines indicate July 1 and August 31 when most of the Fraser River sockeye salmon postsmolts would normally have left the Strait of Georgia.

6.2.2 Queen Charlotte Strait/Sound

During the summer of 2007, the surface layer of eastern Queen Charlotte Sound in the vicinity of Egg Island had the lowest average salinity on record (since 1970) (Figure 69). Summer salinities at Egg Island had generally been lower on average since 2004, but 2007 was an extreme among the recent low salinities. Summer surface waters at Pine Island in Queen Charlotte Strait had the fourth lowest July and August average salinity since 1937. The extreme low salinity anomaly in 2007 was relatively widespread in the region. Repeated measurements from DFO ship surveys of average surface salinity along a transect from Triangle Island eastward in June and July from 1998 to 2009 found that 2007 was the most extreme fresh anomaly (Figure 70).

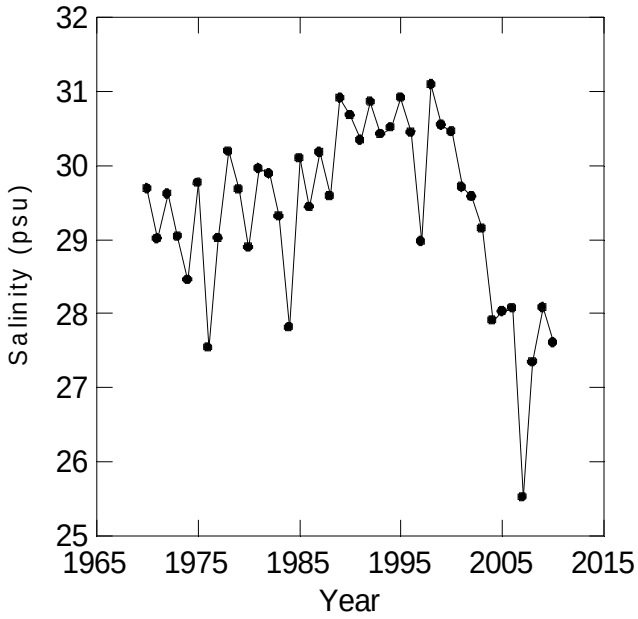

Figure 69: Average of daily salinity measurements at Egg Island (eastern Queen Charlotte Sound) in July and August from 1970 to present. Data maintained by DFO.

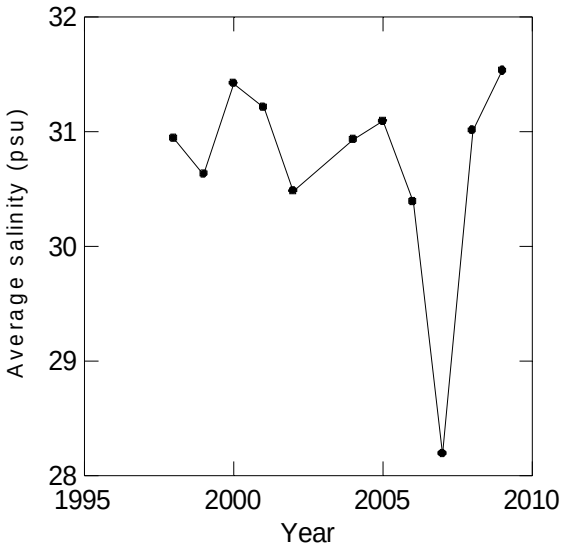

Figure 70: Average surface salinity along a transect from Triangle Island eastward in Queen Charlotte Sound from 1998–2009 (no cruise in 2003). Data courtesy of Marc Trudel (DFO).

The unusual layer of low salinity water that appeared in Queen Charlotte Strait/Sound in the summer of 2007 was caused by extremely high river discharge volumes from snow melt combined with high precipitation in early June of 2007. The accumulation of snow in coastal mountains during the winter of 2006/07 was exceptional and major flooding was anticipated.[xv] Furthermore, the water content in the snow was much higher than normal. Cool weather during April of 2007 delayed/diminished the melt and accumulated more snow such that when the seasonal warming accelerated, the volume of meltwater was extreme. A significant storm in early June added considerable amounts of rain on the melting snow, but its effect was largely restricted to northern rivers (Skeena, Bulkley) and the northern part of the Fraser watershed. Fraser River discharge, while higher than normal in 2007, did not increase to record levels, as was expected in 2007. Discharge from the Wannock River (Rivers Inlet), a major freshwater source in eastern Queen Charlotte Sound, and the Klinaklini River (upper Queen Charlotte Strait) were the highest on record in July 2007 (Figure 71). The consequences of large volumes of freshwater on the surface of Queen Charlotte Sound/Strait are considered further in Section 6.4.

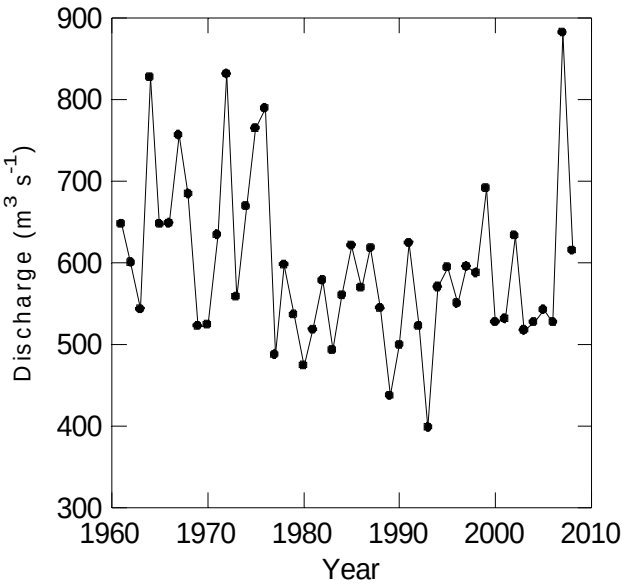

Figure 71: Discharge from the Wannock River (Rivers Inlet) in July. The highest peak occurred in 2007. Data from Environment Canada.

Wind speed and direction in the Queen Charlotte Sound region can be approximated from the monthly average wind speeds at 52.5°N 130°W from the NOAA/NCAR NCEP re-analysis, a database that includes estimates of global monthly average wind speeds from 1948 to present on a 2.5° lat./long. grid. It is evident from these data that extreme wind anomalies can be added to the list of oceanic extremes that occurred in Queen Charlotte Sound in the summer of 2007. July 2007 had either the highest average southeasterly flow in the 63 year time series. A strong southeasterly flow is the typical

xv http://www.ec.gc.ca/meteo-weather/default.asp?lang=En&n=C6C96BEE-1

winter wind pattern along the coast of British Columbia. These winds cause ocean surface waters to be pushed into Queen Charlotte Sound, raising coastal sea levels, and generally enhancing poleward flow of surface water along the B.C. coast. This wind regime caused the warm, low density surface layer in Queen Charlotte Sound to be retained within the Sound. The southeasterly wind anomaly in June 2007 was nearly as strong such that when the average is computed for both months, it is arguably the largest southeasterly wind anomaly in the record (Figure 72).

The appearance of higher than average sea levels in Prince Rupert during the summer of 2007 confirms the response of the ocean to southeasterly winds (Figure 73). It may also explain why the coast of Southeast Alaska was so warm during the summer of 2007. Southeasterlies cause/enhance poleward surface flow along the coast, thereby advecting the generally warmer southern coastal waters poleward.

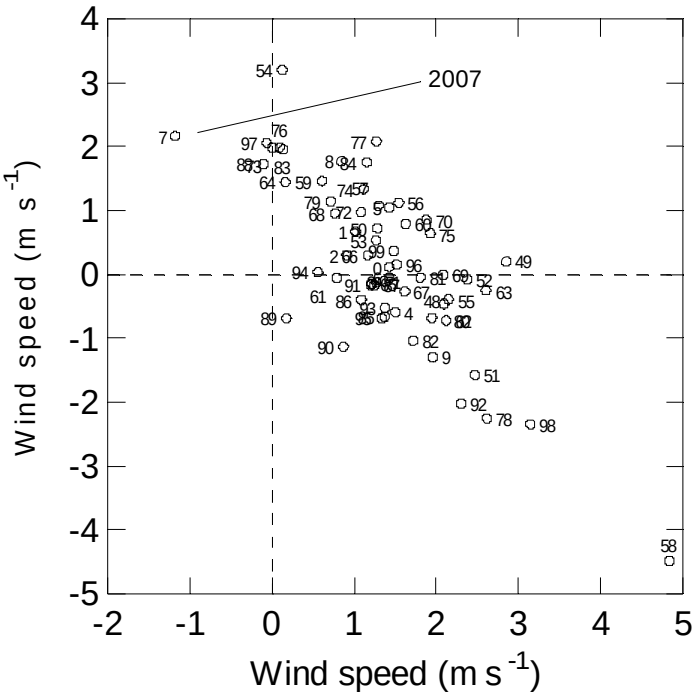

Figure 72: Average June/July wind speed and direction over Queen Charlotte Sound, from 1948. Negative values of the ordinate (left of the vertical dashed line) are easterlies. Positive values of the abscissa (above the horizontal dashed line) are southerlies. Plot point labels indicate year. June/July 2007 was either the strongest southeasterly regime in 63 years, or the second strongest depending on how 1954, with its stronger southerly than easterly component, is ranked. Southeasterly winds tend to retain water within Queen Charlotte Sound so the extreme freshwater discharge was retained in the Sound.

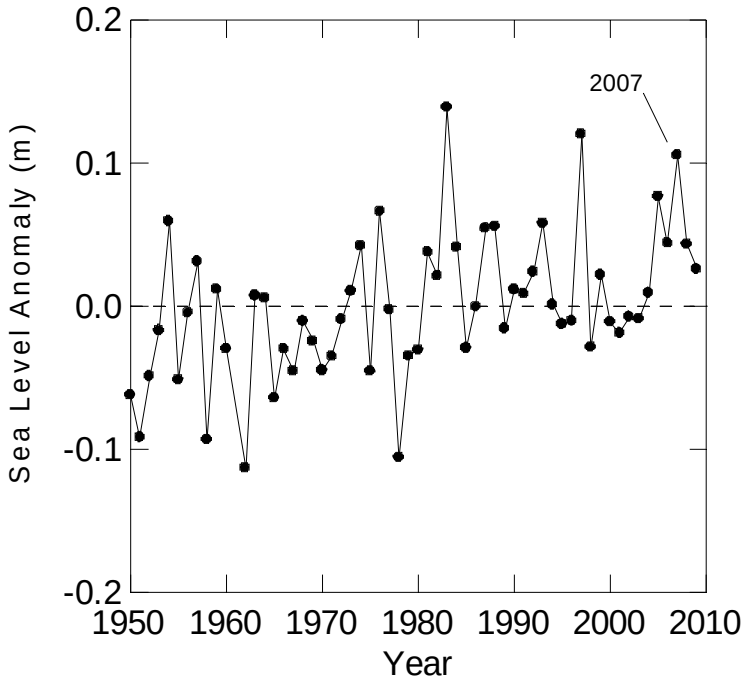

Figure 73: July sea level anomalies at Prince Rupert from the 1950–present average values, based on tide gauge data. Source: DFO/MEDS online tide gauge archive.

Along the North American coast, the summers of 2007 and 2008 were very different in character. July of 2007 began with neutral to positive SST anomalies along the entire coast (Figure 74). These strengthened in August and persisted at slightly lower levels through September. The warmest anomalies occurred on the northwestern side of Vancouver Island, also the location of the Kains Island lighthouse. Daily data collected at the lighthouses reflected the large-scale pattern of warm SST that existed along the coast. Warmer than average coastal temperatures are normally a sign of lower than average survival of Fraser River sockeye salmon[178, 179].

The summer of 2008 was the opposite of 2007 (Figure 74). Sea surface temperatures along the North American coast were cool following what was the coldest year in the Gulf of Alaska since 1972[180], and these cool anomalies persisted along the coast through September. Unlike the Strait of Georgia, migrating sockeye salmon in 2008 would have had a very different thermal experience during their migration in 2008 compared to 2007 once leaving the coastal straits. The temperature of surface seawater along the coast is often an indicator of major ecological changes that accompany the warmer/colder ocean[146].

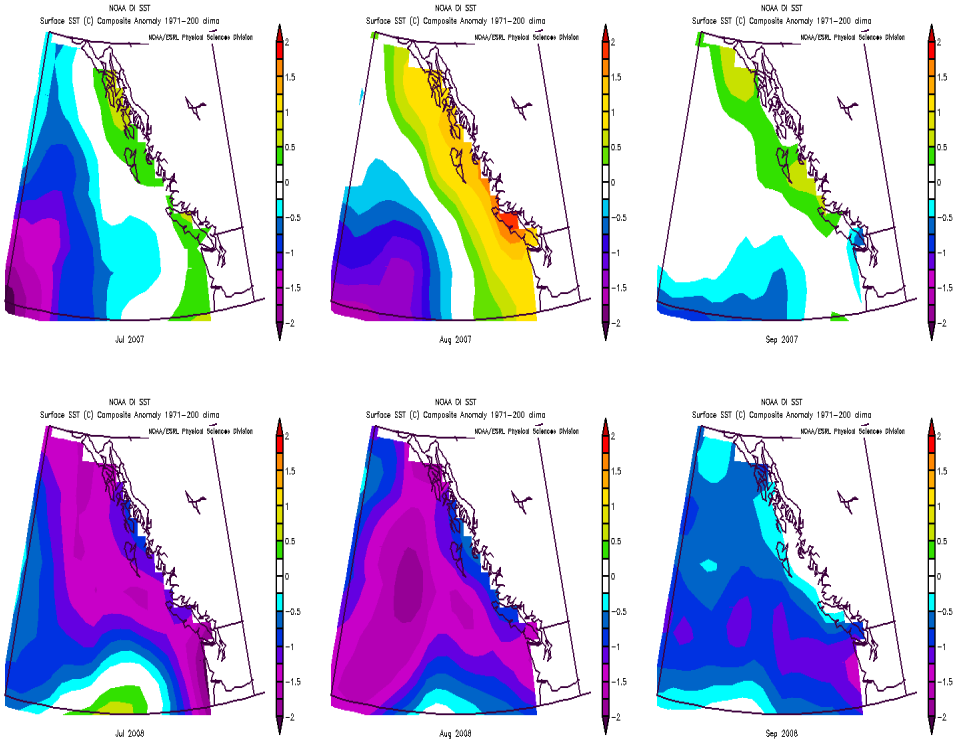

Figure 74: Eastern Gulf of Alaska monthly sea surface temperature anomalies (from 1971 to 2000 average) or (left to right) July to September in 2007 (top row) and 2008 (bottom row). Data are NOAA OIv2SST monthly averages.

The migration route of Fraser River sockeye salmon follows the continental shelf northward from Vancouver Island to Alaska. SST anomalies along the migration route in 2007 were warmer than average along most of the route (Figure 74), especially in August. Many summers have warmer than average temperatures in summer, so what was unique about 2007? The data that were used to produce Figure 74 are monthly average SST, determined from 1°x1° lat./long. grid points. By selecting the grid points that abut the coast, it was possible to compute the average SST along the expected migration route from northern Vancouver Island through Southeast Alaska. However, it is known that the average SST in August is highly correlated with the average SST in July, just as the average SST in July is highly correlated with the average SST in June. This autocorrelation was removed by analysis of covariance of average summer SST (July-August), using May as a covariate, along with latitude. The result of this analysis indicated that July and August 2007 was the most atypical year since 1982 (Figure 75). The summer temperatures in 2007 were the largest outlier from what May SSTs might have predicted. The second most unusual summer occurred in 1997 but it is known that this was associated with the intense el Niño that year. If the postsmolts from Barkley Sound, Columbia River, and other West coast locations were migrating along this part of the West coast, the warm anomalies through Southeast Alaska does not appear to have affected their survival.

Considering the individual 1° × 1° lat./long. SSTs along the migration route, three coastal grid points in Queen Charlotte Sound had the warmest (unadjusted) observed monthly SST (since 1981) in August 2007. While other grid points along the coast were warmer than average by August 2007, Queen Charlotte Sound was the only area that had the most extreme absolute SST in this database. The abrupt shift from negative to strong positive SST anomalies in the daily lighthouse data on the West coast (Figure 67), but not in the Strait of Georgia, is suggestive of a different water mass but not sufficient to reject alternative explanations associated with heat fluxes. Salinity anomalies on the West coast of Vancouver Island were positive rather than negative.

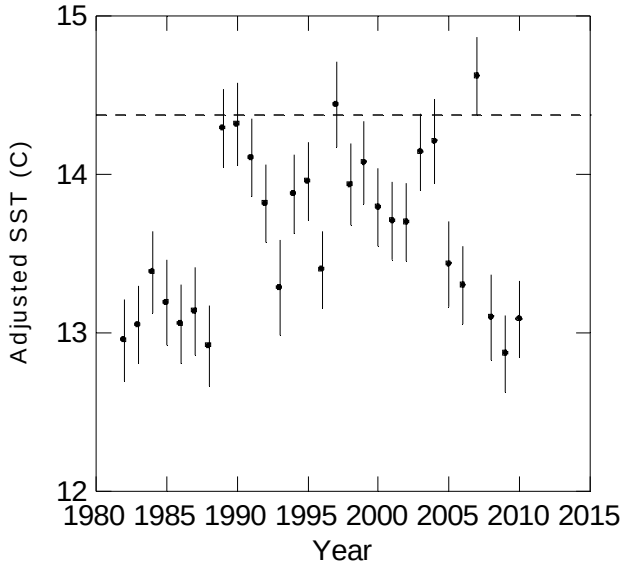

Figure 75: The dots represent average adjusted July and August sea surface temperature in the 1 × 1 lat./long. grid points along the North American coast from Vancouver Island through Southeast Alaska (after removing autocorrelation by including May sea surface temperature as a covariate in an analysis of covariance). The bars represent the 95% confidence intervals. Dashed horizontal line is the lower bound on the estimate of the mean value for 2007 and where it crosses other vertical lines of other years, there is no statistically significant difference between these years.

6.2.3 Coastal biological oceanography beyond the Strait of Georgia

The arrival of spring varies from year to year in the Gulf of Alaska[181, 180], and in the Queen Charlotte Sound/Strait region[182]. Unless migratory predators like the sockeye salmon adjust their migration to match inseason production, emergence, or seasonal migrations of prey species into the region, they will face different prey fields from year to year. The spring chlorophyll bloom occurs first in coastal waters where nearby sources of freshwater facilitate the early development of water column stability. The dominant feature in SeaWiFS ocean colour satellite images of the region is the contrast between coastal and offshore waters (Figure 76). The subdominant feature is the spatial variability among years. Year to year variability in the mean is evident, but it is difficult, at this scale, to see why 2005 and 2007 would produce the worst returns on record.

April surface chlorophyll$_a$ concentrations derived from SeaWiFS ocean colour satellite remote sensing

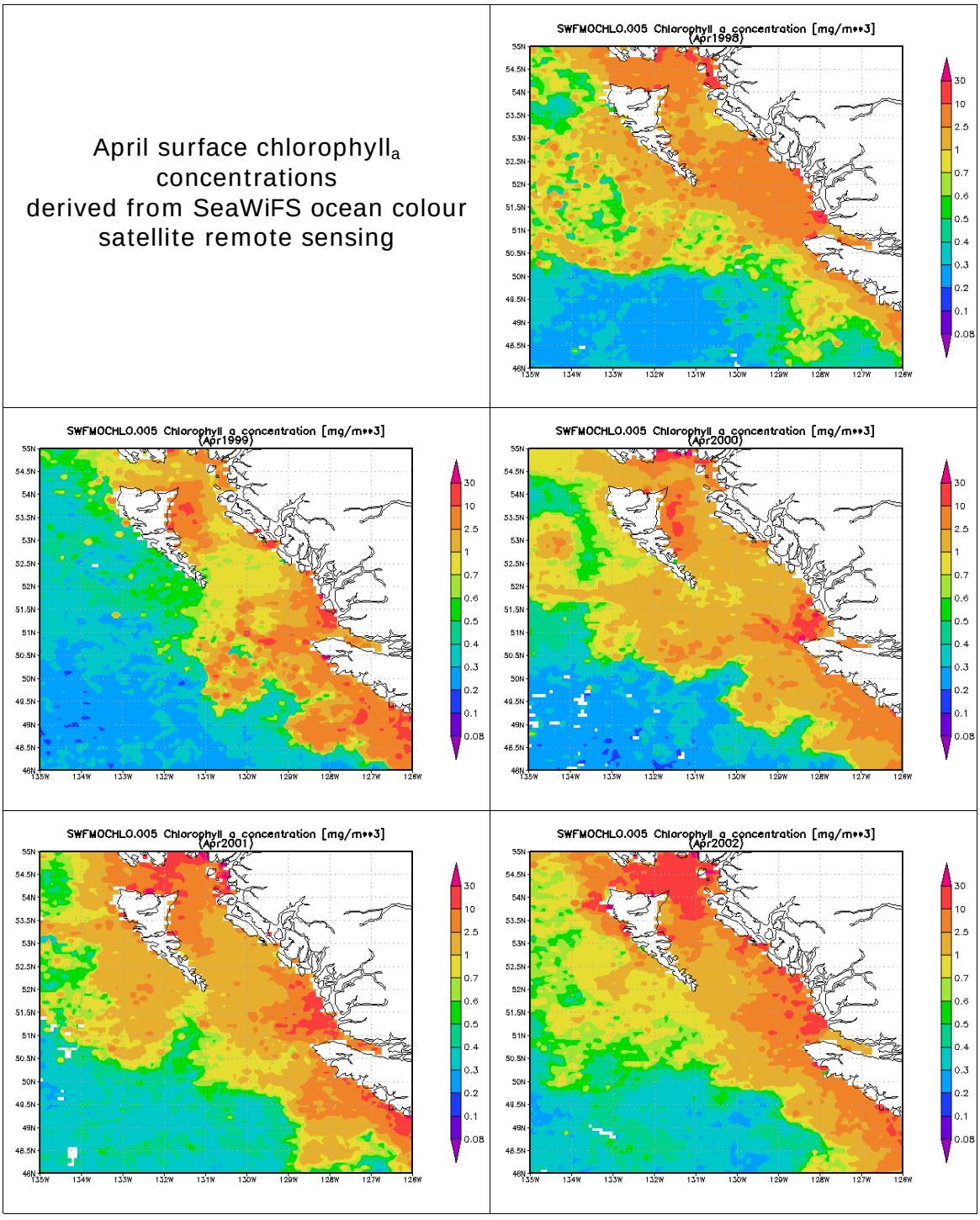

Figure 76: Average surface chlorophyll concentrations from Queen Charlotte Strait to Dixon Entrance in Aprils (2001–2008). White regions over water indicate where cloud cover precluded generating an average value. Analyses and visualizations used in this figure were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC.

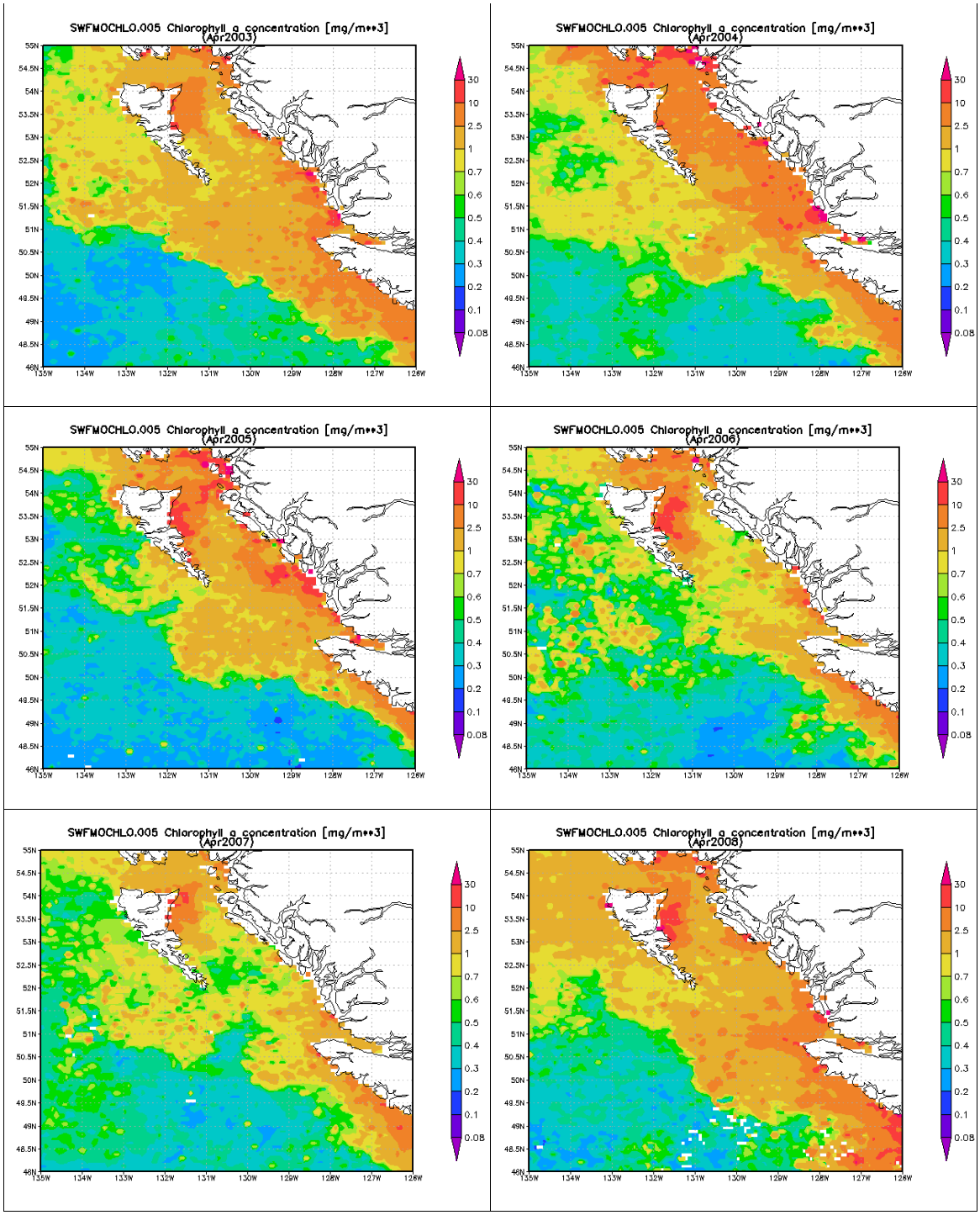

Figure 76: Continued.

A high correlation was reported between average chlorophyll concentrations (which reflect phytoplankton densities) in Queen Charlotte Sound (Figure 77) during the first three weeks of April and Chilko Lake sockeye salmon marine survival from 1998 to 2007[183] (Figure 78). The remarkable contrast in average chlorophyll concentration between years in this month reflects the state of development of the spring bloom. In years when the spring bloom is delayed, marine survival of Chilko Lake sockeye salmon is low. The bloom in 2007 was the latest in the record since 1998. While there is likely no Fraser River sockeye salmon in Queen Charlotte Sound during April, the lag until their arrival in June and July can allow time for their prey base (e.g. euphausiids) to develop.

Another predator in Queen Charlotte Sound that feeds at a similar trophic level to sockeye salmon postsmolts is Cassin's auklet (*Ptychoramphus aleuticus*). It has a breeding colony on Triangle Island (50°52′ N 129°05′ W) in the Scott Islands chain off northern Vancouver Island at the entrance to Queen Charlotte Sound. Its diet is planktivorous, feeding primarily on copepods and euphausiids[182]. The timing of the zooplankton biomass peak is more important than year-to-year variation in biomass in determining the availability of a preferred prey, *Neocalanus cristatus*[184]. Cassin's auklet fledgling production in 2007 was not atypical[185, 186]. The western position of Triangle Island in Queen Charlotte Sound may have placed it beyond the range of greatest influence of high runoff, such that its feeding opportunities were more similar to those experienced by Barkley Sound and Columbia River sockeye salmon than by Fraser River sockeye. Two piscivorous species of seabirds which also breed on Triangle Island had their lowest recorded breeding success in 2007[185].

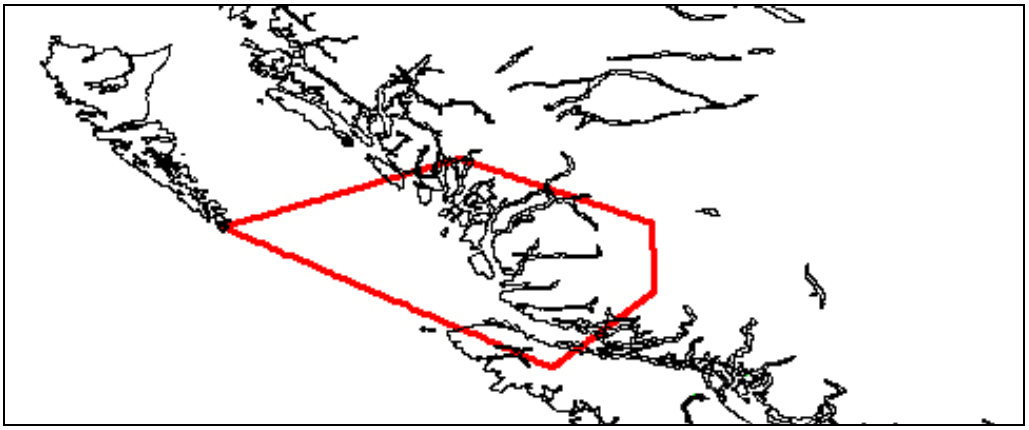

Figure 77: Spatial domain used to generate a high correlation ($r^2 = 0.87$) between Chilko Lake sockeye salmon survival and SeaWiFS chlorophyll a concentration in the first 3 weeks of April from 1998 to 2007[183].

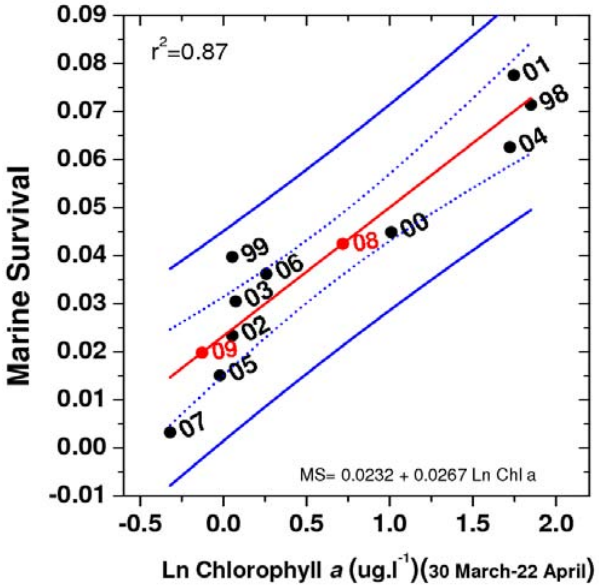

Figure 78: Annual marine survival of Chilko Lake sockeye salmon versus chlorophyll concentrations in Queen Charlotte Sound (log transformed) during the first three weeks of April. Reproduced from Irvine et al.[183]. Plot point labels indicate ocean entry years.

6.3 Gulf of Alaska

6.3.1 Large-scale climate processes

A characteristic feature of the surface of the North Pacific Ocean is its tendency to persist in warm or cold phases, sometimes for decades[137]. The phenomenon is known as the Pacific Decadal Oscillation (PDO). It has been observed that a warm phase in the Gulf of Alaska is accompanied by a cold phase in the central and western North Pacific, so the system is recognized as a large-scale climate phenomenon. In recent years, the alternation between positive and negative phases has occurred more frequently[180]. The negative phase of the PDO is associated with cooler SSTs along the North American continent[137]. From 2003 to 2008, abrupt changes in short-term climate preclude establishing a clear climate regime in the Gulf of Alaska[168]. The generally warm years of 2003 to 2005 were followed by generally cold years from about 2007. The winter of 2008 was one of the coldest in the Gulf of Alaska in 35 years (Batten et al. 2010). The negative phase of the PDO re-emerged in October 2007 and persisted until the 2010 El Niño. Summer temperatures from 2003 to 2005 in the Gulf of Alaska were among the warmest on record and their appearance coincided with a shift in factors that affect North Pacific climate.

The cold seasons (November–March) of 2003 to 2005 had relatively high sea level pressure (SLP) over western North America from B.C. to California. The consequence for the Gulf of Alaska was anomalous low-level winds from the south, accompanied by relatively warm and wet weather. The cold seasons of 2006 to 2008 had anomalously high SLP extending from the Bering Sea to the U.S.

mainland, with a small but prominent area of low SLP in the northwestern Gulf of Alaska. This configuration produced a cold flow of air from the Northwest in the western Gulf of Alaska and a relatively stormy environment in the central and eastern parts. The warm seasons (April–October) of 2003 to 2005 had relatively weak SLP anomalies with a tendency for higher (lower) than normal SLP in the western (eastern) half of the Gulf, indicating generally weak wind anomalies from the North. On the other hand, the warm seasons of 2006–2008 featured generally high SLP in the northwestern U.S. mainland, with low SLP over the Gulf. This pattern generates modest storminess and upwelling in the central part of the Gulf of Alaska[168].

The NINO3.4 index is a measure of SST along the Equator in the central Pacific Ocean (Figure 79). It is generally accepted as the basis for evaluating the state of the el Niño/Southern Oscillation climate phenomenon. The index was positive during the el Niño in the winter of 2002/03, generally positive through to the el Niño in the winter of 2006/07, and mostly negative during the La Niña in the winter of 2007/08. The PDO index reflects the dominant spatial pattern of SST in the North Pacific. Positive (negative) values of the PDO index are associated with warmer (cooler) SST anomalies along the North American coast. The PDO index (Figure 80) tracked the NINO3.4 index quite closely but with a slightly more prominent decreasing trend. The decline in the PDO index was accompanied by a concomitant decline in the SST along the western coast of North America from the Bering Sea to Baja California. The North Pacific Gyre Oscillation (NPGO)[187] is the subdominant ocean/climate pattern in the North Pacific (not shown). A positive phase of the NPGO tends to be associated with anomalously strong equatorward flow in the California Current and relatively strong cyclonic flow along the periphery of the Gulf of Alaska. It was positive in 2003 and negative by about 2005. The North Pacific Index is an atmospheric index that reflects average SLP over the North Pacific (not shown). It was negative in 2003 in association with an anomalously deep Aleutian Low, and then varied with season, with a tendency for positive values from 2006 to 2008. The eastern North Pacific Ocean experienced the full range of atmospheric and oceanic variability from 2003 to 2008.

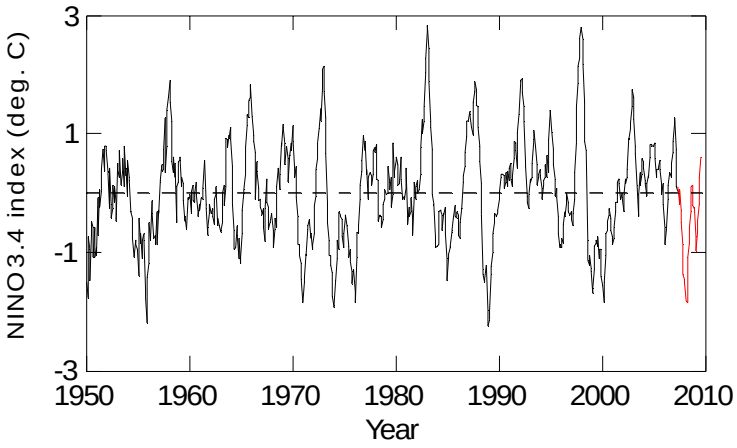

Figure 79: NINO3.4 index from 1950 to 2009 (June). Red line indicates the period when the 2005 brood year was at sea. Large negative values indicate la Niña and large positive values indicate el Niño.

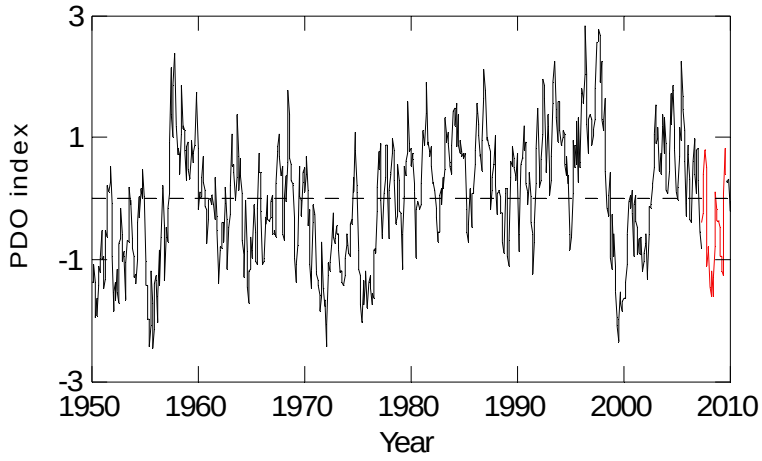

Figure 80: Pacific Decadal Oscillation (PDO) index computed from sea surface temperature data for the period 1950 to 2009, inclusive. Red line indicates the period when age-1.2 sockeye salmon from the 2005 brood year were at sea.

6.3.2 Sea level pressure

SLP anomalies in the Northeast Pacific Ocean in 2007 were negative especially in July 2007 (Figure 81). Given the position of the centre of these anomalies, between two climatological features, it reflects a both a weakened Subtropical High and an enhanced Aleutian Low for this month. Negative anomalies persisted through the summer of 2007, whereas sea level pressure anomalies in June 2008 were generally above average, lower in July although neutral over Vancouver Island and the U.S. West coast, and negative in August. Broad-scale low pressure anomalies over the Gulf of Alaska in August of 2008 may have played a role in the anomalous chlorophyll blooms that occurred that summer[188].

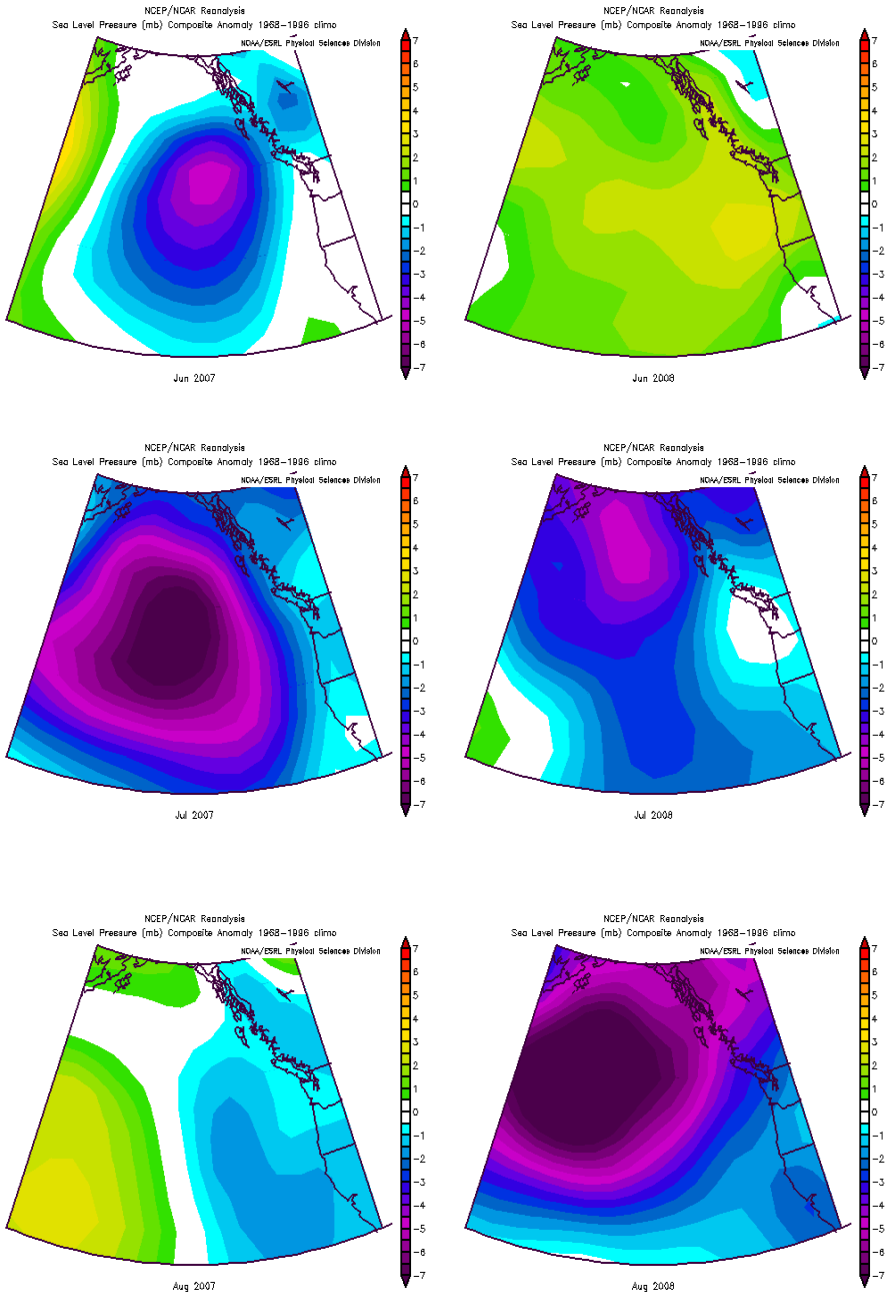

Figure 81: Monthly averaged sea level air pressure anomalies for June–August 2007 (left) and 2008 (right).

6.3.3 Ocean circulation

The North Pacific Current is a large-scale feature of ocean circulation in the North Pacific Ocean. It follows an eastward path in the mid-latitudes from the Asian coast, crossing the Pacific before bifurcating into the poleward Alaska Current, and the equatorward California Current[170]. On average,

the location of this B.C. Bifurcation is Vancouver Island, however, from month to month the strengths of these currents vary (Figure 81). An index of the strength of the North Pacific Current[171] indicates that at the end of 2006, the North Pacific Current was enhanced and mean values stayed higher, on average, than were found in the earlier part of the time series that began in 2002. The maximum value occurred in June 2008. More of this enhanced circulation found its way into the California Current which is reflected in the low value of the Alaska Current:California Current strengths (Figure 82, red line) and in the greater similarity of the California Current index to the North Pacific Current index during this period.

The strength of the Alaska Current varies according to variation in atmospheric circulation, especially during the stormier cool/cold seasons[189]. A recent review of atmospheric patterns in the North Pacific from 2003 to 2008 found that average winter SLP was higher in 2007 and 2008[190] which reflects fewer or less intense storms. In the Gulf of Alaska, high SLP is associated generally with colder winters because enhancement of the winter atmospheric circulation during stormier winters tends to bring more of the warmer air from the south to the Gulf of Alaska.

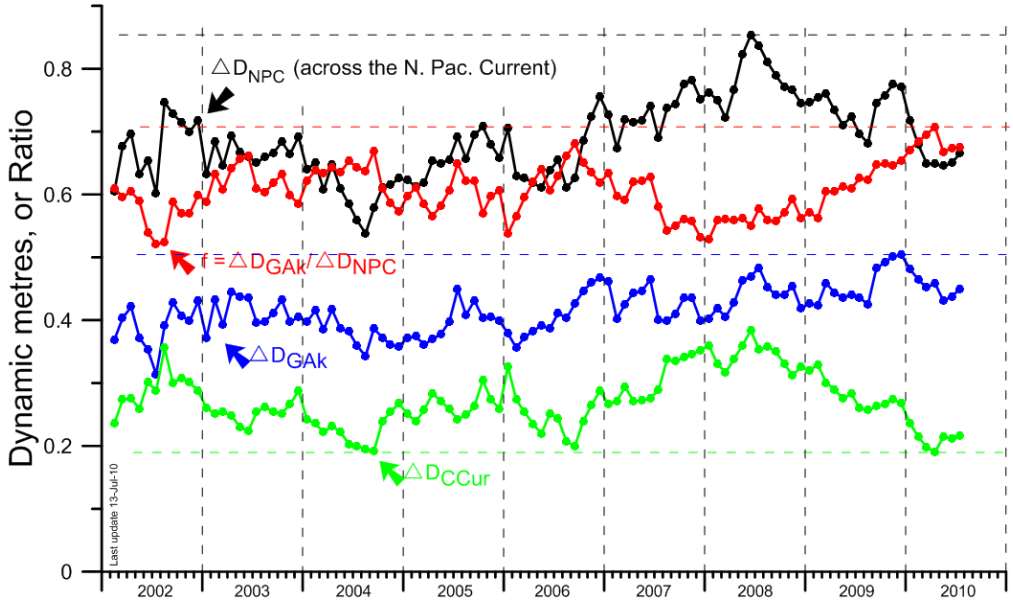

Figure 82: Monthly indices of the strength of the North Pacific Current (black), Alaska Current (blue), and California Current (green) and the ratio of Alaska Current:California Current (red). Source: http://www.pac.dfo-mpo.gc.ca/science/oceans/Argo/Argo-currents-courants-eng.htm

6.3.4 Hydrography

Physical forces (sun, wind, tides, gravity) and the properties of seawater (temperature, salinity) affect the extent of vertical mixing in the uppermost part of the ocean. In winter, when turbulent forces are greatest, the entire water column is mixed down to 100 m or more (Figure 83, panels 1–4). Vertical mixing is an important component of ocean ecology because it is the major source of the nutrients (e.g. nitrate, phosphate, silicate, iron) that are required for phytoplankton growth in the spring. With the

advent of Project Argo, it is now possible to examine the characteristics of vertical mixing in the World Ocean at much finer resolutions of time and space than at any time in history.

In the Gulf of Alaska from 2003 to 2010 the average depth where the maximum change in seawater density occurred was deepest in April (Figure 83, panel 4). As the surface of the ocean warms in spring, it becomes less dense at the surface. As the winds abate the depth of mixing becomes significantly shallower. Indeed, it occurs so rapidly that a frequency distribution of mixed layer depths is strongly bimodal. Through the month June, for example, the Gulf of Alaska had 62% of profiles during these years with surface mixing only to shallower summer mixed layer depths while 38% remained mixed to winter depths (mean = 107 m). Some profiles indicated the remnants of winter mixing into July (Figure 83, panel 7). Surface cooling in autumn causes seawater to become denser and with the onset of autumn storms in September, the process of deepening the mixed layer is initiated.

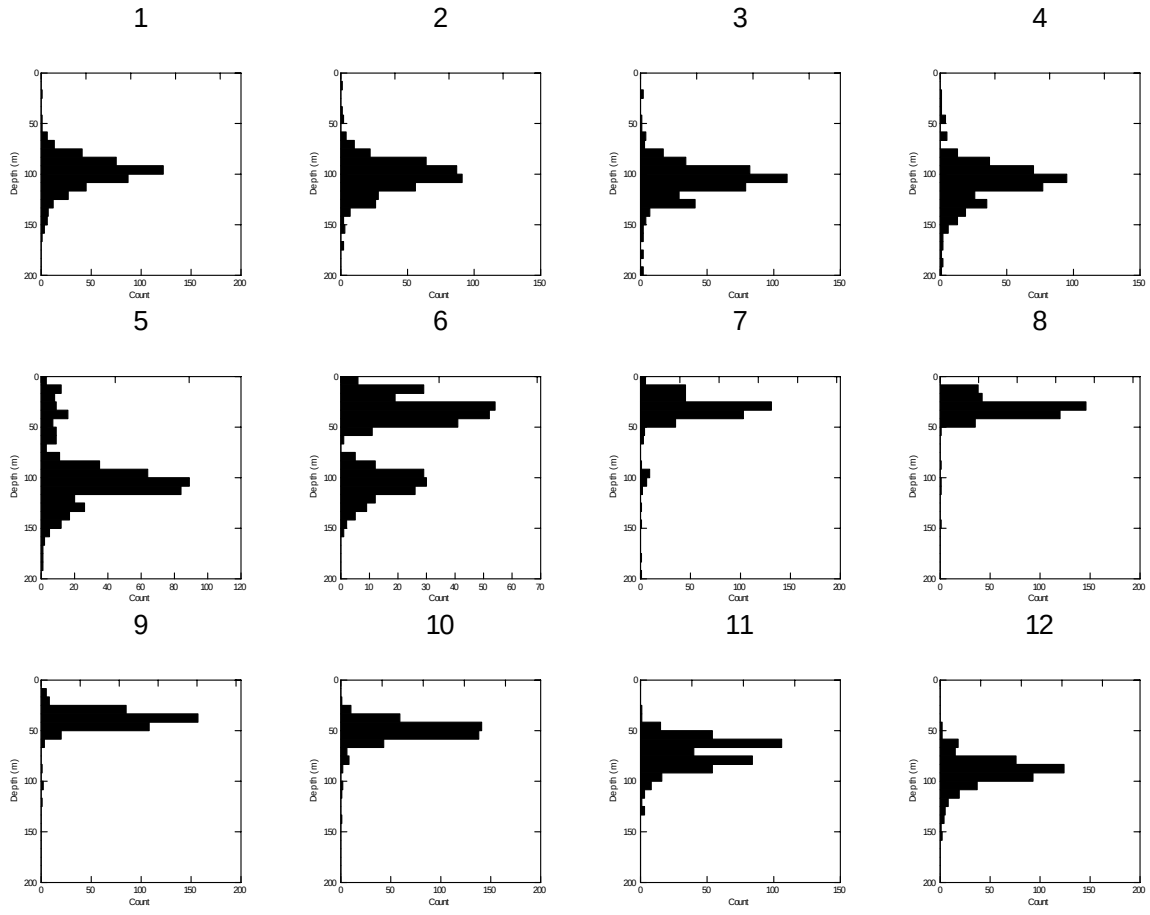

Figure 83: By month, frequency distributions of depth at which the maximum rate of change in water density occurred in Argo profiles in the Northeast Pacific (>50°N, <160°W) from 2003 (January) to 2010 (May).

Much of what has been reported historically about the oceanography of the Gulf of Alaska has been a result of sampling along Line P, Juan de Fuca Strait to Station Papa[191]. It has been considered that vertical mixing reaches its deepest extent in the Gulf of Alaska in March[192], rather than in April as was indicated by the Argo profiles from 2003 to 2010. The difference is likely due to the broader coverage provided by the Argo floats and their more northerly locations compared with Station Papa (50°N 145°W) where most of the historical oceanographic work has been conducted.

Figure 83 is based on all Argo profiles from 2003 to 2010 taken east of 160°W and north of 50°N. Pooling the data over such a large area fails to account for regional variation in mixing dynamics within the Gulf of Alaska, and the statistics fail to account for the variable distribution of floats in the Gulf of Alaska each year. These difficulties take on greater significance when considering observations for an individual year. Maximum mixed layer depth on the continental shelf on the Seward Line (Alaska), for example, occurs in January[193].

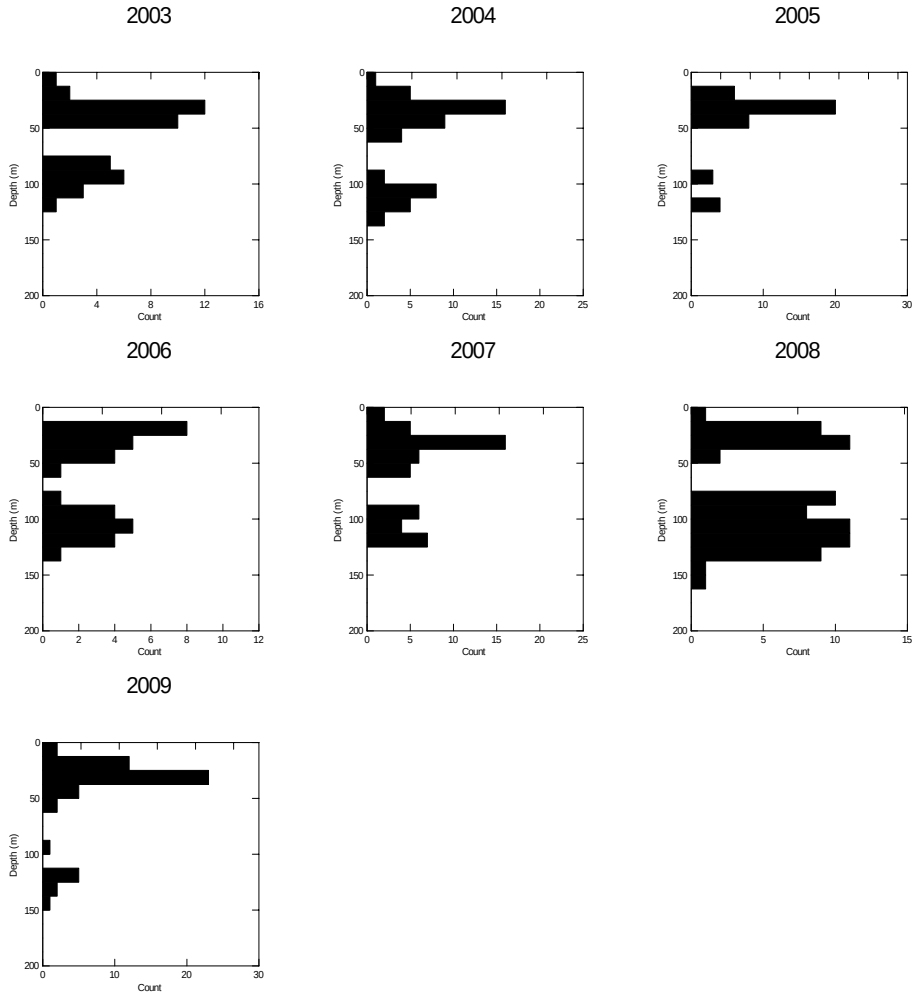

Figure 84: As in Figure 83, but for the month of June only, by year.

Because the frequency distribution of the depths of maximum vertical density gradient is bimodal in spring, it suggests a relatively abrupt onset of shallow mixing depths. The greatest degree of bimodality occurs in the month of June (Figure 83). From 2003 to 2009 the proportion of Argo profiles, indicating that deep winter mixing was occurring in June versus the number indicating shallower summer mixing, varied from year to year (Figure 84). June of 2005 and 2009 had the smallest proportion (both 17%), indicating deep mixing while June 2006 had the largest proportion (45%) of profiles, indicating deep winter mixing in June.

At the depth where the maximum rate of change in density occurs, the magnitude of the change in density at that point is an index of the degree of water column stability. In July and August, the warm summer of 2005 had the most stable summertime water column whereas the summer of 2006 had the least stable water column. Only the summer of 2005 stands out as an unusual year among this collection of summers (Figure 84).

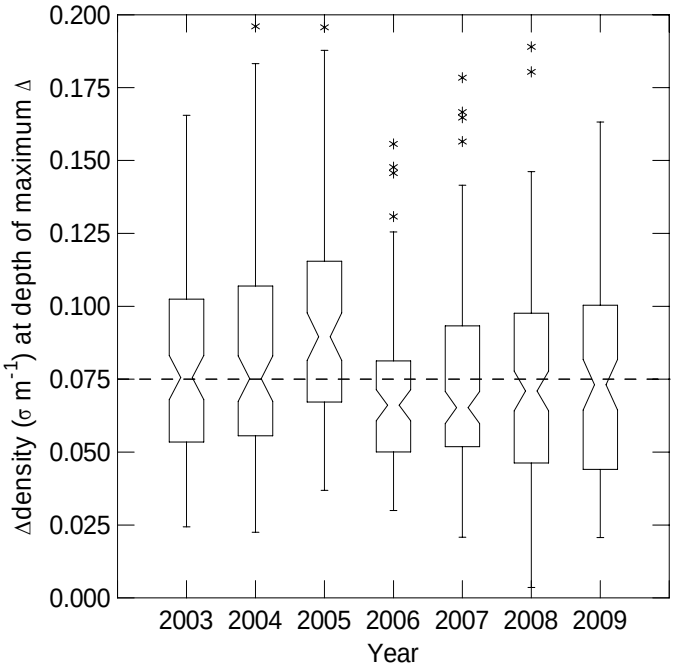

Figure 85: Box and whisker plots of the magnitude of change in seawater density at the point of maximum change in each profile, July and August combined. The narrowest point of the box is the median value. If the indented portions of the notch (narrowed parts of the box) do not overlap between years, the median value is considered to be statistically different between years. For example, the bottom of the notch in 2005 is greater than the top of the notch in 2006 so the median values of the two years are statistically different. An dashed horizontal line appears at 0.075 to aid the eye to distinguish differences in the locations of the statistical features across years. The symbol ✶ indicates outliers, in this case much stronger rates of change in density than were found in other profiles.

6.3.5 Physical spring in offshore Gulf of Alaska

Gargett[156] developed a simple index of water column stability that considers the density difference between the 0–20 m depth layer and the 60–80 m depth layer within a single hydrographic profile. Using Project Argo data from January 2003 to June 2010, the average Gargett Stability Index (GSI) was computed within each 5° latitude × 10° longitude block north of 45°N and east of 160°W, by week, based upon whatever profiles were found within each year/week/block. A loess smoother of GSI versus week was applied each year to these averages. The dominant spatial pattern has water column stability lowest in the blocks adjacent to the North American coast and deepest in the block of longitude farthest from the coast. By arbitrarily choosing a value of the GSI that is approximately midway through the developing seasonal stability (GSI = 0.1), it is possible to compare the phenology of the process each year (Figure 86). From 2003 to 2010, the achievement of this level of stability ranges over a period of between 5 to 6 weeks, between 160–150°W. The block between 150–140°W has about the same range of weeks and seasonal development. The range is about 7.5 weeks from 140–130°W, largely because of the late seasonal development in 2008 (Figure 87). The range of weeks between the earliest year and the latest year was greatest (9.5 weeks) to the east of 130°W, again because of the 2008 outlier.

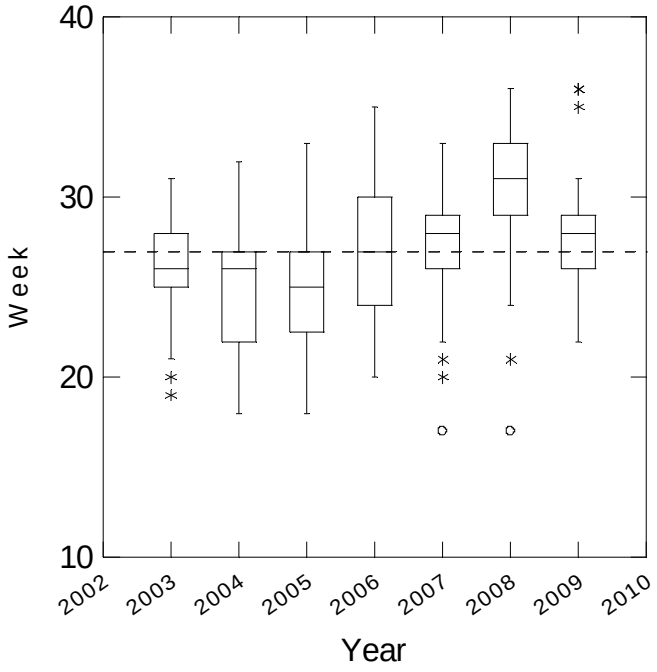

Figure 86: Box and whisker plot indicating interannual variability in the establishment of water column stability. The values summarized in this figure are the weeks, within 5° × latitude 10° longitude blocks, when a Gargett Stability Index exceeds 0.11, for all such blocks east of 160°W, north of 45°N. The earliest year was 2005 (week 25) and the latest year was 2008 (week 31). The symbol ∗ indicates outliers and the symbol º indicates strong outliers. Original data are from Project Argo.

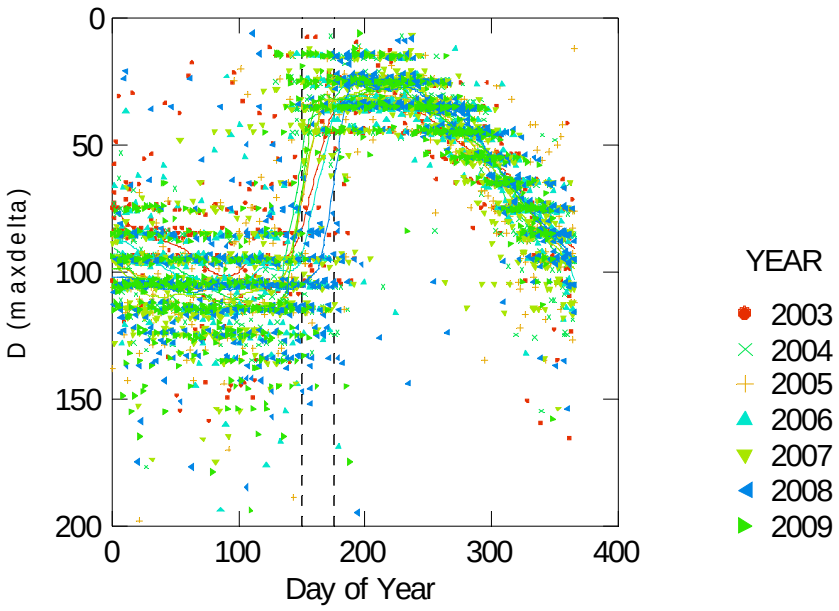

Figure 87: Depth of the maximum rate of change in seawater density in Argo profiles by day of year from 2003 to 2009. Dashed vertical lines indicate approximately the earliest and latest (2008) years in the loess trend lines, a difference of 26 days.

6.3.6 Nutrients

The depth of vertical mixing in the Gulf of Alaska in winter is important because it provides the dominant source of nutrients for primary production in spring. As nutrient concentrations tend to increase with increasing depth, the depth of the winter mixed layer will affect the concentrations of nutrients such as phosphate, nitrate, silicate, and iron. The availability of the latter regulates primary production in the open waters of the Gulf of Alaska[194, 195].

Following a two year (1995–1997) period of monitoring surface nutrient concentrations in the North Pacific from a vessel of opportunity that began in 1987, Wong et al.[196] reported little interannual variability in the seasonal nutrient cycle. While there was a period during the 1990s when nutrient re-supply to the surface layers was reduced at Station Papa[197], near the southern limit of sockeye salmon distribution, nutrient concentrations there have tended to be at or above average from 2003–2008[180].

A major biological "event" occurred in the Gulf of Alaska during the summer following the emigration of the 2008 smolt year (Figure 88). Its cause has been attributed to the widespread deposition of volcanic ash in the Northeast Pacific following the eruption of Kasatochi (52.2°N 175.5°W) in the Aleutian Islands chain on August 7–8, 2008[188]. The oceanic response to adding iron of volcanic origin was enhanced primary production (Figure 88) where iron is the limiting nutrient in the Northeast Pacific. Both the 2007 and 2008 smolt years of Fraser River sockeye salmon were in the Gulf of Alaska at this time. Assuming that the immature sockeye salmon distributions in the Gulf of Alaska in 2008

were what they were in the 1960s, immature fish would be feeding in the deep water regions of the Gulf of Alaska that summer. The enhanced productivity of chlorophyll in mid to late August likely provided little immediate benefit to immature sockeye salmon, as they do not eat diatoms. The dominant copepods, with an ability to sequester the enhanced production as stored lipids, would have entered diapause at depth by mid-August.

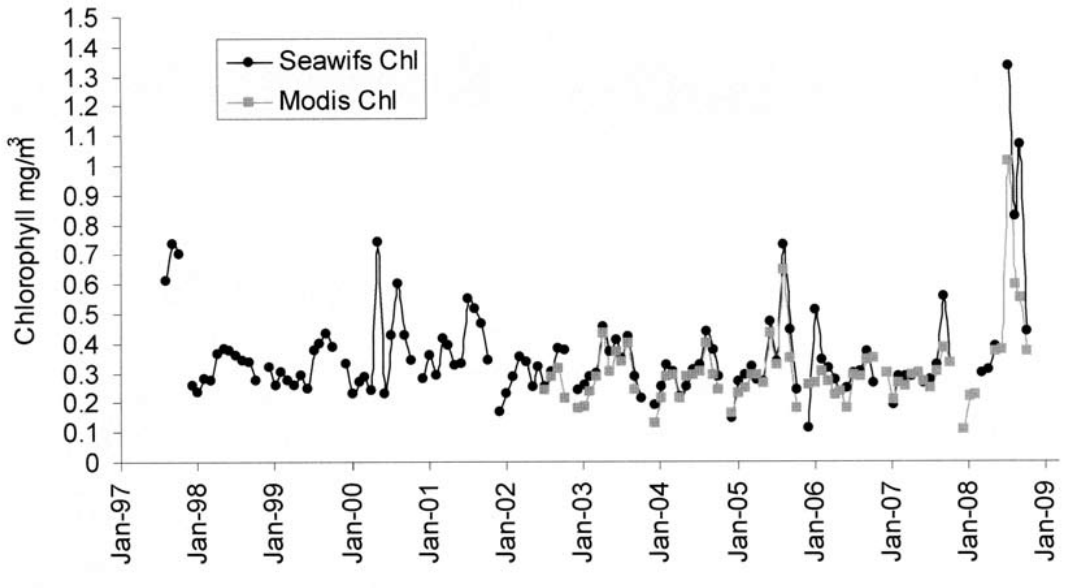

Figure 88: Satellite-derived chlorophyll concentrations for a region of the NE Pacific centred on Station Papa from the MODIS and SeaWiFS satellites. Produced with the Giovanni online data system, developed and maintained by the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC). Reproduced from Batten et al.[180].

Based on current knowledge, the abundant 2008 smolt year would have been migrating along the continental shelf. In this region, iron is not normally the limiting nutrient[198] so its addition would not have produced much benefit to this cohort in 2008. To have a direct benefit on the 2008 smolt year, the enhanced biological production would need to be entrained in the pelagic food web and stored through, or made available to it over, the winter. Data from the Continuous Plankton Recorder (CPR) program indicated that zooplankton biomass in 2009 was near the average[199].

6.3.7 Biological spring

Broad-scale spatial patterns of chlorophyll concentration in the Gulf of Alaska are similar from year to year with chlorophyll concentrations in the deeper waters at much lower levels than the coastal region, although the influence of the coastal zone extends beyond the limits of the shelf.

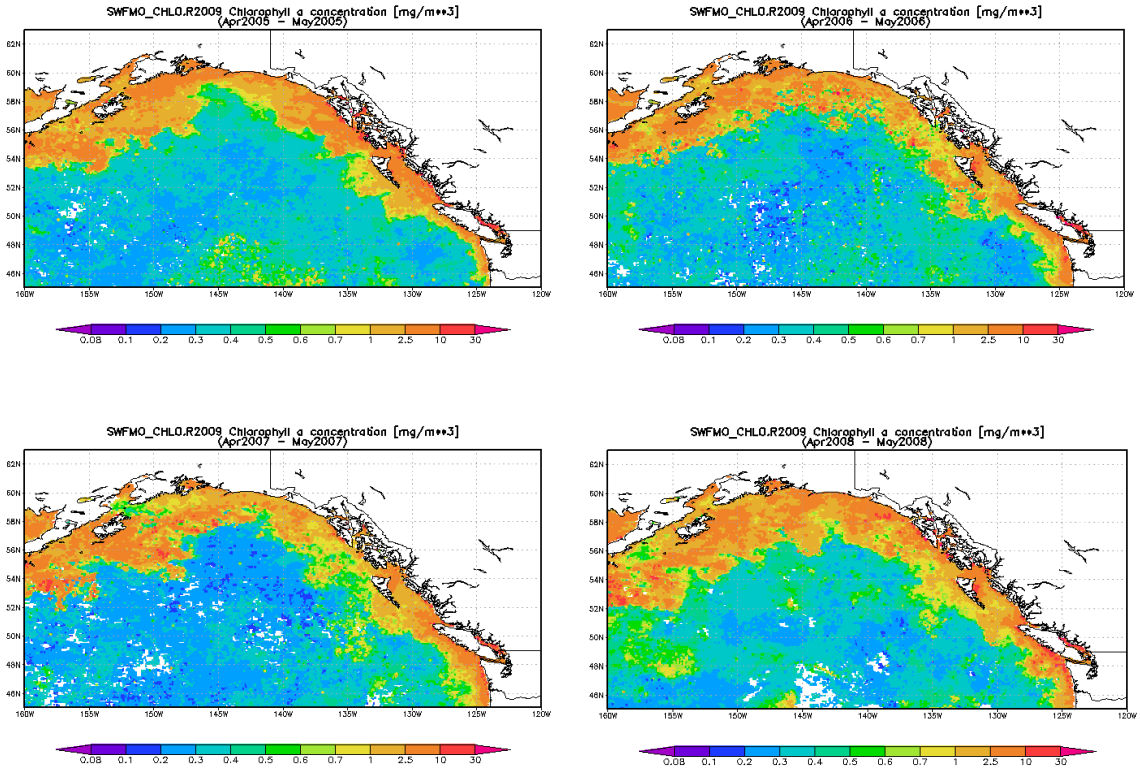

Figure 89: Average surface chlorophyll concentrations in the Gulf of Alaska in April/May (2005–2008). The two ocean entry years of worst survival are contrasted in the left column. White regions over water indicate where cloud cover precluded generating an average value. Analyses and visualizations used in this figure were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC.

Year-to-year variation in the onset and development of physical spring in the Gulf of Alaska affects a biological/ecological response[181]. The most abundant meso-zooplankter in the Subarctic North Pacific, for example, is the copepod, *N. plumchrus*. It is a small planktonic crustacean (<1 cm) with a one year life cycle, and grows by moulting through a series of stages from egg to nauplius to copepodite to adult. Prior to the adult stage, the final copepodite stage migrates to depth where it moults to the adult stage to reproduce after a summer of feeding and growing near the surface[181]. The eggs are laid at depth where they hatch and the nauplii migrate to the surface in spring to repeat the cycle. The annual migration in spring of immense numbers of these animals from depth to the surface provides food for their predators. Their annual arrival at the surface is correlated with sea surface temperature[200], but this empirical association between warmth and migration may be just a proxy for water column stability[181]. Winter-like temperatures can persist in the Gulf of Alaska because of deep vertical mixing. When the water column stabilizes by radiant heating, it reduces the volume of water circulating near the warmer surface air temperatures providing a positive feedback that reinforces the density gradient.

From 2003 to 2008, the timing of peak zooplankton biomass in the Gulf of Alaska was reflected in the variability of the physical ocean[180]. The annual biomass peak was early in the warmer years of 2003 to 2005, and the period spent at the surface during these summers was less. The peak biomass in colder years was later, with a more extended period at the surface, especially in 2008 (Figure 90). The abundances of species of Subarctic copepod and cool-water chaetognaths increased with upper-ocean cooling and with increases in the strength of the North Pacific Current.

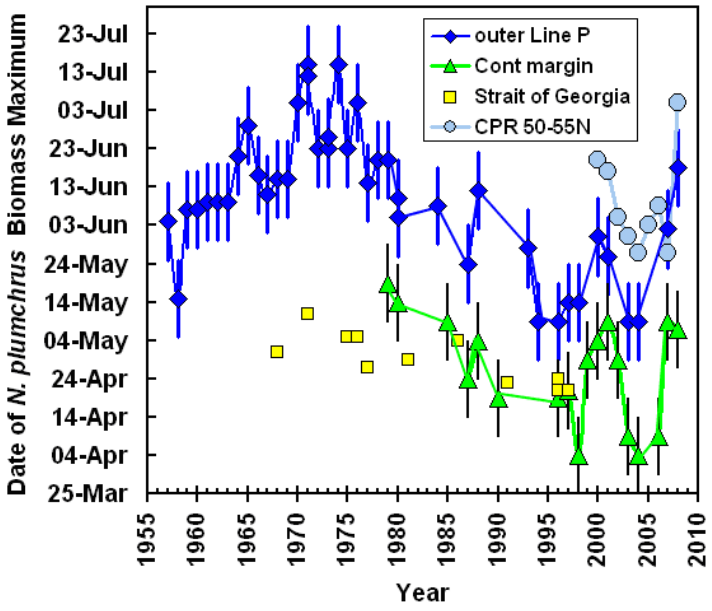

Figure 90: Phenology time series for *Neocalanus plumchrus* populations in four subregions of the Northeast Pacific. Figure reproduced from Batten et al.[180].

Summary – The seasonal peak in zooplankton biomass in 2008 had not developed as late since the 1970s when they occurred commonly. It was confirmed in two independent zooplankton observation programs located in different parts of the Gulf of Alaska (Line P and the CPR program) so the phenomenon was relatively widespread. Therefore, it is not unreasonable to propose that the delayed timing would have affected many of the sockeye salmon populations in the region in a similar manner. The stomachs of immature sockeye salmon on the high seas do not normally contain large fractions of copepods (See Section 4.2) because they generally feed at a higher trophic level.

6.4 Extreme Sea Surface Temperatures

NOAA data servers provide access to a 1° × 1° lat./long. grid of global monthly averaged SSTs from late 1981 to the present. These data were used to determine where or if there were any extreme monthly SSTs (high or low) while the 2007 smolt year was at sea. At each grid point, the historical record was searched to understand, for each calendar month, what year had the highest and what year had the lowest average SSTs in the record. A simple outcome of this exercise is an understanding of how many grid points had extreme values in each year (Figure 91).

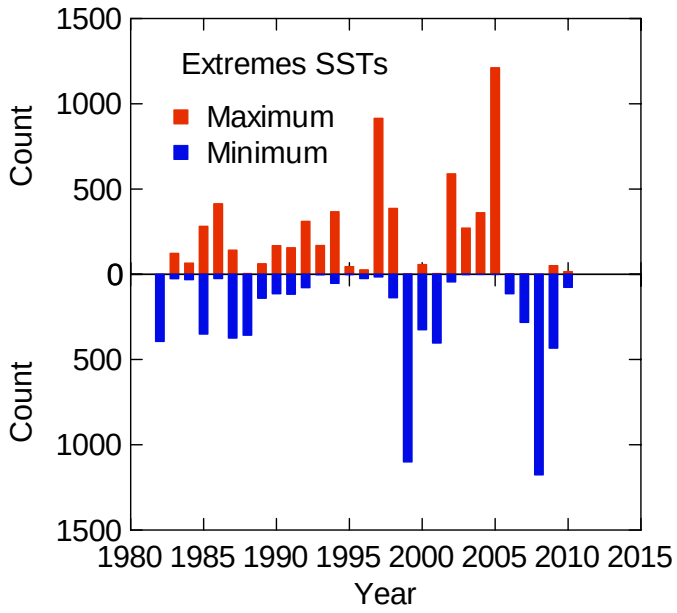

Figure 91: Annual number of grid points with extreme sea surface temperatures in the Gulf of Alaska (>45°N, <160°W) from 1982.

From these data, it is possible to understand that SSTs have tended to exhibit more extreme monthly averages in the latter half of the record (beginning with the 1997/98 el Niño. The two years showing the most positive extremes were 1997 and 2005. These years were associated with later than average return timing of Fraser River sockeye salmon, especially in 2005, but not reduced survival. The two years with the most negative SST extremes were 1999 and 2008. There was also a tendency for the Gulf of Alaska to persist in either positive and/or negative phases. So the period when the 2007 smolt year was at sea was a period dominated by cold extremes, with the greatest number occurring in 2008. Within 2008, most of the extremes occurred in winter/spring, especially May. The only location in the entire Northeast Pacific with maximum historical (since 1981) temperatures in 2007 occurred in August in the area of Queen Charlotte Sound (Figure 92).

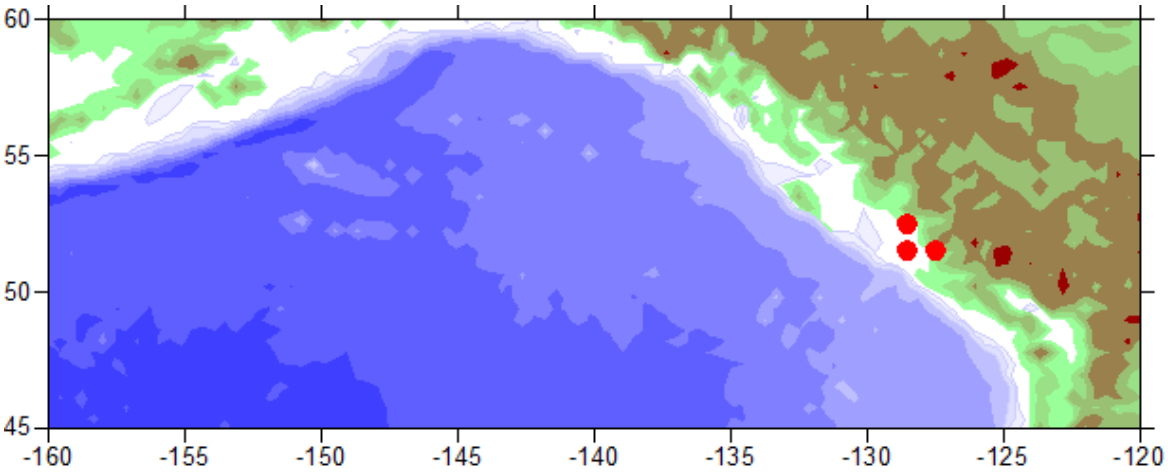

Figure 92: Locations of the most extreme, positive sea surface temperatures in the Gulf of Alaska during the period 1982 to 2010 that occurred in 2007. All maxima (red dots) observed in 2007 occurred only in Queen Charlotte Strait/Sound during the month of August.

6.5 Future of the Gulf of Alaska

Coupled ocean–atmosphere climate models are used to evaluate both the present behaviour (dynamics) of the climate system, and to predict its possible future states. Currently, the best known example of the use of these kinds of tools is the climate projections made by the IPCC concerning the future of Earth's climate. A shortcoming of the global models for use in studying coastal ecosystems is their relatively low resolution of these models. However, the global climate models can be used to downscale high-resolution regional models for the region of interest. One such set up is based on the Regional Ocean Modeling System (ROMS) which is used to downscale global climate models to the Northeast Pacific Ocean (NEP). ROMS is a free-surface, hydrostatic, terrain-following primitive equation ocean circulation model whose core was developed at Rutgers University and UCLA, with significant contributions from a large community of users. It has several advanced features including efficient parallelization for sustained performance on multi-processor computers, and numerous data assimilation capabilities.

6.5.1 NEP ROMS model description

The NEP model domain extends from approximately 20°N to 71°N and about 2250 km seaward of the North America west coast at a horizontal resolution of 10 km with 60 terrain-following vertical levels stretched towards the surface boundary. The terrain-following coordinate system has distinct advantages for modeling shelf regions. The full vertical coordinate system is compressed over the shelf resulting in high vertical resolution in a region of interest (shelf regions) and as a consequence, no computations are wasted in the deeper ocean. The grid is a rectangle, in a Lambert Conical projection, to reduce the amount of computation of wet cells over land.

For the historical analysis of model performance, it was run for the period from 1958 through 2004. The surface forcing for the NEP model is derived from the datasets for Common Ocean-ice Reference

Experiments version 2 (CORE v2), which produces 6-hourly winds, air temperatures, sea level pressure and specific humidity, daily and short-wave and downwelling long-wave radiation, and monthly precipitation. Riverine inputs are implemented as surface freshwater which guarantees global conservation over long time scales. Boundary and initial conditions for this domain were derived from the Simple Ocean Data Assimilation (SODA 2.0.2) which is an ocean reanalysis product for the 1958 to 2006 period. The nominal spatial resolution of SODA is 0.5° and five day averages were used for the boundary conditions. The northern boundary of the domain has a sink term which is set to enforce a 0.8 Sv northward transport through the Bering Strait.

Tidal forcing is implemented through the boundaries using the eight dominant diurnal and semi-diurnal components derived from Oregon State Tidal Prediction Software[201]. Good simulations of tides require a good representation of the bathymetry, so a new Alaska region bathymetry was used. It was constructed solely from observational soundings blended with a conventional ETOPO dataset for the regions south of 45°N. To generate outlooks of future climate of the Gulf of Alaska, the A2 scenario[101] from the Geophysical Fluid Dynamics Laboratory model was used.

6.5.2 Model sea surface temperature

Monthly climatologies of SST under the A2 CO_2 emissions scenario were computed by calendar month from the NEP5 climate ocean/climate simulation results for two periods, 2000–2010 and 2040–2050. These climatologies were differenced, month by month, to see how average SSTs might change between the present and 2050 (Figure 93). The run of this model suggests that much of the Subtropical and Transition Zone regions of the northeastern North Pacific will be warmer by 2040–2050 and they appear to have expanded into the Gulf of Alaska[202]. Nevertheless, there is considerable spatial and seasonal variability in the response of the Gulf of Alaska to enhanced CO_2 emissions.

An interesting result of this model of the Northeast Pacific Ocean is that average SST became cooler than at present along a broad expanse of ocean adjacent to the North American coast during the cold season, and in late summer by 2040–2050 (Figure 93). The reduction of average SST during the cold season is due to a reduction in the cyclonic winds (Aleutian Low) that are responsible for the poleward advection of warmer surface water from the South. From May through July, however, average SSTs are generally warmer by 2040–2050 along the British Columbia and Southeast Alaskan coasts, suggesting poorer marine survival of Fraser River sockeye salmon. July is the month when they emerge onto the continental shelf and the consequence of warmer SST is usually poorer survival. By August, however, SSTs cooler than at present prevail along the coast because of enhanced winds producing upwelling throughout the Gulf of Alaska coastal areas. This may favour the survival of summer emigration from the coastal straits. Future research will consider the effects of tidal mixing (cooling) in coastal regions that are predicted to be warmer.

Summary - The NEP5 model suggests that within 40 years, the selective pressures on the survival and evolution of Fraser River sockeye salmon populations may favour those individuals that emigrate very early, perhaps in April and May, or those that emigrate later in summer and early fall. The current behaviour of mass emergence onto the continental shelf in July will be less than optimal if the correspondence between warmer than average SST and poor marine survival persists. However, this is only one potential outcome produced by one climate model, so more ensemble runs with more models will be needed to confirm the expected future of SSTs in the Gulf of Alaska.

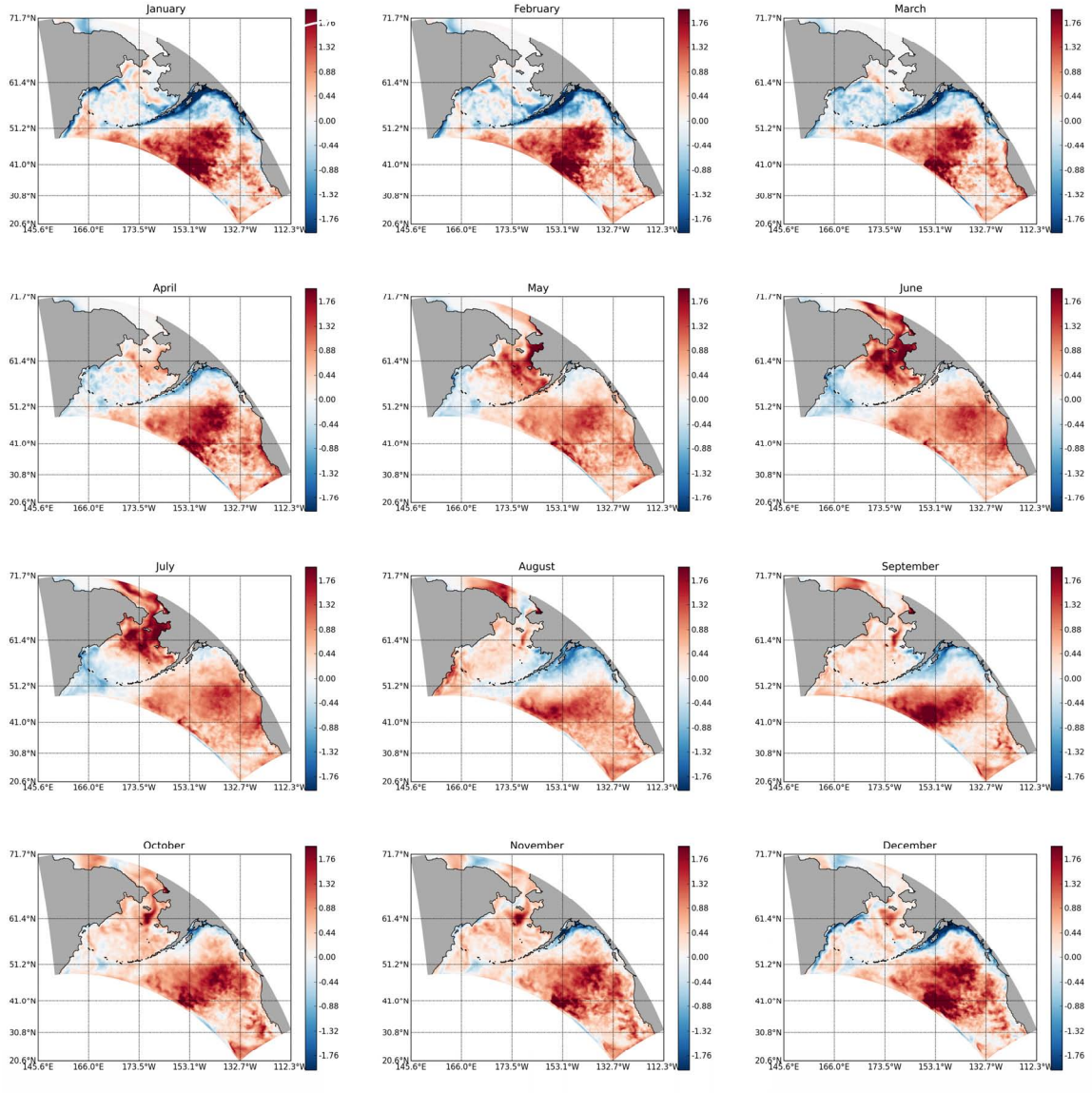

Figure 93: NEP5 model projections of sea surface temperature change, by month, from the 2000–2010 average to the 2040–2050 average based on a single run of the NEP5 model. Red shades indicate regions of warming, blue indicates regions of cooling.

7 Discussion

7.1 Cause of Low Returns in 2009

Key Question 1:
Can the decline in Fraser sockeye in 2009 be explained by the conditions the fish experienced in the marine environment?

Is it explained by the marine environment – no; *can* it be explained by the marine environment – yes. Current understanding of Fraser River sockeye salmon migratory behaviour and that of other less well studied populations is that all postsmolts of all southern populations eventually migrate northward toward the northern B.C./Alaskan coast[10]. What each will encounter on their way to enhanced feeding and growth in Alaskan waters will differ depending on the location of ocean entry and the choice of migratory route. Oceanic conditions that are known to be associated with lower survival of Fraser River sockeye salmon occurred along much of the Fraser River sockeye salmon postsmolt migration route in 2007 where an extremely poor environment developed in Queen Charlotte Sound/Strait prior to and during the migration.

7.1.1 Data shortages

Very little is known about what the sockeye salmon actually experience in the ocean. Observations are not made routinely at the time and space scales of the fish[203]. Impressions of the marine environment are often a result of observations made across broad regional scales at coarse resolution (relative to a sockeye salmon) when measured from satellites. From these data, ideas about what the sockeye salmon might have experienced are based on time–space averages of the environment which ignore finescale variability. The ocean can be, and is often observed from a single location, from which the state of the broader environment is often inferred. Whether a fish experiences what happens at a station depends on the de-correlation scale of the oceanic phenomenon of interest. A large de-correlation scale indicates that observations made at a station are indicative of a broader region than what was measured at the station, whereas small a de-correlation scale indicates that a station reflects only local variability. The scale is typically assumed to be large. Only data storage tags (Figure 42) make it possible to record simple environmental characteristics, such as temperature, pressure (depth), and sometimes location, but these tags tend to be expensive and must be recovered before the results are known. Tag recovery rates from sockeye salmon are often low.

7.1.2 Warm and cool in 2007

> *"Juvenile salmon along the outer Vancouver Island coast generally survived very well in the cool years of 2007 and 2008"*
>
> DFO, 2010

Whether it was cool in 2007 depends on where one looks. Most of the Fraser River sockeye salmon that failed to return in 2009 went to sea as juvenile salmon in May or June of 2007. Salmon in the

California Current system tend to have lower survival when they go to sea in warmer years[178, 146]. The DFO report, cited above, considered 2007 and 2008 to be cool years. The Gulf of Alaska began to cool in 2006, following a very warm year in 2005. By 2008, it had become very cold compared to recent norms[180]. However, on the time and space scales that are likely to affect Fraser River sockeye salmon, and perhaps others using the same migration route, the summer of 2007 was very warm in some important places (Figure 92). There was a strong, abrupt, and generally persistent shift to warm sea surface temperature anomalies along the continental shelf in late June of 2007 (Figure 67). Its magnitude exceeded the typical summer warming that occurs each year along the west coast and it appeared in both coastal lighthouse and satellite SST data. However, as most southern stocks were likely using this migratory route during 2007, and non-Fraser stocks did not suffer incremental mortality, it seems unlikely that this coastwide phenomenon was the cause of incremental mortality of the Fraser stocks. The surface waters of Queen Charlotte Sound/Strait were warmer in August of 2007 than in any other August from 1982 to 2010 and this was the only location in the Gulf of Alaska with high SST extremes in 2007. Sockeye salmon that migrated along the outer coast (including those from the Columbia River) could have avoided the consequences of the phenomenon. The extreme southeasterly wind regime that became established along the West coast in June and July 2007 could have retained the surface layer of warmer, fresher water within Queen Charlotte Sound.

7.1.3 Location of mortality

The emigration of 77 million smolts from Chilko Lake and their low returns in 2009 provides the best evidence, from one of the largest sockeye salmon producers in the watershed, that the mortality occurred in the sea, although the number of smolts that survived the 640 km journey downstream to the Strait of Georgia is unknown. Finding solid evidence for a solely marine source of mortality in populations other than Chilko Lake is more challenging because of a lack of smolt/postsmolt abundance data. Some lakes have in-lake surveys of fry abundance before their last winter in freshwater, but the fraction of total mortality that occurs during the last winter in the lake is not measured[204]. Therefore, all estimates of marine survival and/or productivity of sockeye salmon in the Fraser River include some component of freshwater mortality. In most stocks where only returns per spawner data are available, rates of marine and freshwater mortality are confounded (see Section 7.2.1).

Aggregate returns per spawner for sockeye salmon in the Fraser River watershed were very low for the 2007 smolt year. Most of these fish returned in 2009. Whether it will turn out to be the lowest on record depends to a certain degree on how the calculation is made and after learning the magnitude of the returns of this group in 2010 and to a much lesser degree in 2011. The approach used in the preparation of this report was to use the median annual value of returns per effective female spawner (as natural logarithms), calculated separately for each population. Each population is a genetically distinct entity that has evolved its own characteristics for survival such that each can be considered as an independent experimental trial (to the extent that methods of data collection/processing allow it). The returns observed up to 2009 were augmented by an estimate of the (small) numbers of older fish that are expected to return in 2010 and 2011. When the median values are considered across stocks, the 2007 ocean entry year will likely turn out to be the penultimate year of poor survival for the majority. However, in the specific case of Chilko Lake, postsmolt survival will likely be the lowest on record. Preliminary results from the 2010 returns indicate that the age-at-maturity of the 2005 brood year was not unusually delayed[205], even though the average age-at-maturity of the returns has been getting older in this and some other stocks (Figure 94).

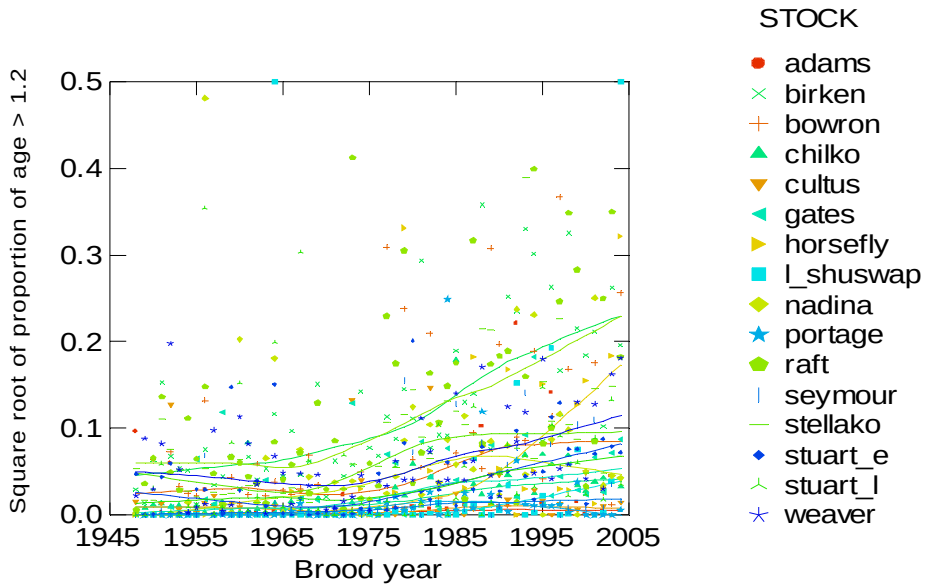

Figure 94: Proportion of brood year returns at age 1.3 and 1.4.

The greatest impediment to demonstrating conclusively whether or not the mortality experienced by the many Fraser River sockeye salmon that went to sea in 2007 (mostly the 2005 brood year) occurred at sea is a lack of adequate observations. Most of the 2005 cohort would have entered the Strait of Georgia in May of 2007. A tiny fraction of non-Harrison River fish may have been collected during coho and chinook salmon surveys in the Strait of Georgia in July 2007, and another tiny fraction was collected further North in the inside straits and on the continental shelf. Acoustic tags that were placed on large hatchery-reared sockeye salmon that were released from Cultus Lake from 2004 to 2007 had similar detection rates as they migrated northwestward through the Strait of Georgia in 2007 as in other years[40]. But for the most part, the survivors were not seen again for 24 months. Only the low returns of jacks (mostly age 1.1) in 2008 after 12 months at sea provided an early glimpse of the fate of these fish. The lack of observations of salmon at sea, at relevant time and space scales, severely limits the ability to draw firm conclusions about their fate[203, 147]. As the low return in 2009 was a rather extreme event, our approach was to look for potentially relevant extremes in the oceanic environment while these fish were at sea.

A comparison of survivals of other species/stocks with similar life-histories is one approach to understanding what occurred between 2007 -2009. There is a significant but weak positive correlation between the annual estimates of postsmolt survival of age-1.x Chilko Lake sockeye salmon and the average marine survival of wild and hatchery age-1.x coho salmon released into the Strait of Georgia in the same smolt year[206]. This information may be of some value because the marine survival of these coho salmon postsmolts is known one year earlier than the equivalent group of Fraser River sockeye salmon. Strait of Georgia coho salmon marine survival has persisted at low levels for decades. For the 2007 ocean entry year, the pattern of low survival continued, but it was not an extremum.[xvi]

xvi Coho survival data spreadsheet by S. Baillie, DFO, pers. comm.

Some progress has been made to understand the kinds of ocean states that are associated with poor or good survival in the sea across multiple trophic levels[146]. Composite indices of ocean state have been developed from physical and biological oceanographic data, and these are showing promise in contributing to improved forecasts of salmon returns in some places. For example, the "Mackas Ecosystem Productivity Index" or MEPI (Figure 93) indicated that the state of the coastal ocean off Vancouver Island was near average or tending slightly toward cool and productive in the spring of 2007[207]. However, the locations and seasons of the variables used to develop the MEPI could have reflected the state of the coastal ocean that was experienced by West coast sockeye salmon stocks, rather than that experienced by Fraser River stocks leaving via Johnstone Strait.

Official forecasts of Fraser River sockeye salmon return abundance do not include measurements of the state of the oceanic environment[208]. Beginning in 2007, an informal annual salmon forecasting forum was established to record and review forecasts as part of the annual coastal salmon ocean ecology meeting. Forecasts of salmon returns generally ranged from poor to good for 2009 but only sockeye salmon expectations were singled out as not expecting good returns[209]. Whether this was simply a coincidence or a skillful forecast will require more years of trials.

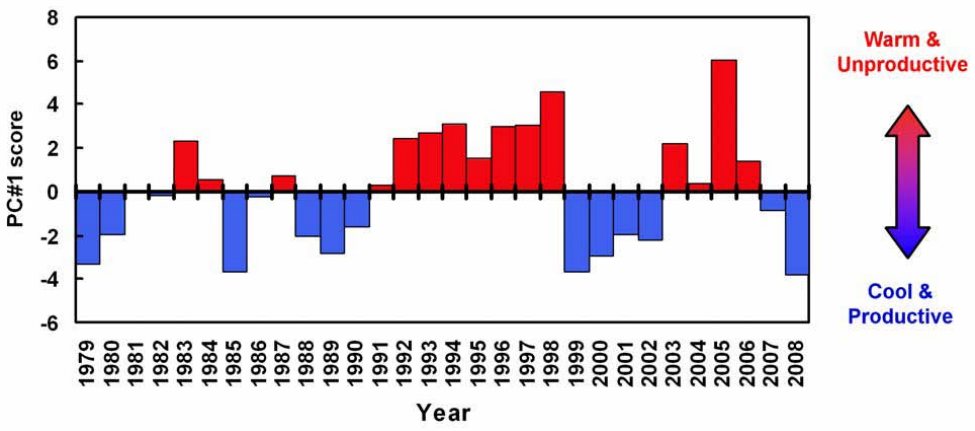

Figure 95: Mackas Ecosystem Productivity Index (MEPI) in coastal waters off Vancouver Island.

7.1.4 The Harrison River anomaly

> *"Harrison Sockeye from the 2006 brood year that returned as three year old fish in 2009, exhibited below average productivity (preliminary estimate). Harrsion [sic] Sockeye from the 2005 brood year that returned in 2009 as four year old fish and in 2008 as three year old fish, exhibited the lowest productivity on record for this stock.*
>
> DFO, 2010

Most sockeye salmon from the Harrison River migrate into the Strait of Georgia as underyearlings, which distinguishes them from most other populations in the watershed. The preliminary estimate of returns to the Harrison River for underyearlings that entered the Strait

of Georgia in 2007 is approximately 1.5 million fish[xvii] which is approximately four times the previous maximum. The majority of these fish would have spent the summer of 2007 in the Strait of Georgia, where they were found in September sampling to be rather abundant[210]. This suggests that the Strait of Georgia was the not the location of mortality of the 2009 returns of age-1.2 sockeye salmon. It would require conjuring a mechanism that keeps one ecotype alive and abundant while killing the rest. Harrison River sockeye salmon likely avoided the fate of the other ecotypes in 2007 by their normal habit of delaying migration from the Strait of Georgia and/or by emigrating via Juan de Fuca Strait to the west coast where they are typically the only Fraser River sockeye salmon found in fall samples[10].

7.2 Decline in Marine Productivity or Change in Distribution?

Key Question 2:
Is there any evidence for declines in marine productivity or changes in Fraser sockeye distribution that can be associated with the 15 year gradual decrease in Fraser sockeye productivity?

- **Gradual decline –** The idea of a gradual decline in average productivity is a better model fit[xviii] than a "shift" to lower productivity in only 3 of 16 stocks (Adams, Bowron, Stellako). In 12 stocks, a shift to lower productivity in 1992 provided a better fit. In one population (Raft), they are equally likely models. This may also be the case where the data cannot distinguish between the two models, but there was insufficient time for a more rigorous assessment. An accurate characterization of the nature of the decline is an important first step in searching for a cause.

- **Marine productivity –** In the open ocean, there is no trend in average nutrient concentrations in the southern Gulf of Alaska (Station Papa) since the 1950s, no trend in average chlorophyll$_a$ since 1998, and no trend in average zooplankton biomass.

- **Distribution –** Progress is being made to improve the knowledge of the coastal distribution of juvenile Fraser River sockeye salmon, but sampling to date has not been sufficient to make year-to-year comparisons in regional stock composition. The oceanic distributions of populations of Fraser River sockeye salmon are not known with sufficient accuracy to understand if they have varied from year to year or decade to decade. Surveys conducted in the Gulf of Alaska during the 1950 and 1960s by the Fisheries Research Board of Canada were never repeated after the Board was disbanded.

xvii http://www.psc.org/NewsRel/2010/NewsRelease11.pdf
xviii Lower sum of squared deviations.

7.2.1 Interpreting returns per spawner

The lengthy histories of returns per spawner provided by the Pacific Salmon Commission demonstrate a striking pattern of variation and co-variation in productivity in Fraser River sockeye salmon over the past six decades (Figure 96). Some authors have argued that variation in Fraser River sockeye salmon productivity is a reflection of winter climate variation in the Northeast Pacific affecting sockeye salmon survival in the ocean[139, 211] while others have demonstrated very little, if any of this effect on Fraser River stocks[212, 203], and one author found that declining productivity in Chilko Lake through the early 2000s was a result of lower freshwater survival[135]. Increasing the average number of spawners in Chilko Lake in the 1990s did not translate into an equivalent increase in the numbers of smolts leaving there. So the fundamental question concerning productivity is whether patterns of variation have arisen in freshwater, saltwater, or both. Returns per spawner time series do not necessarily reflect where a change has occurred.

The one place where this evaluation can be attempted, without making strong assumptions, is in Chilko Lake. In this case, it is clear that attributing all of the variation in total survival to shared variation in the sea would be a mistake[135]. In fact, over the history of observations of the Chilko Lake population, variation in returns per spawner appears to be almost equally shared by freshwater and marine (postsmolt) effects (Figure 97). Bootstrapping each of these comparisons separately indicated that the correlations in the two panels of Figure 97 are not significantly different (Figure 98).

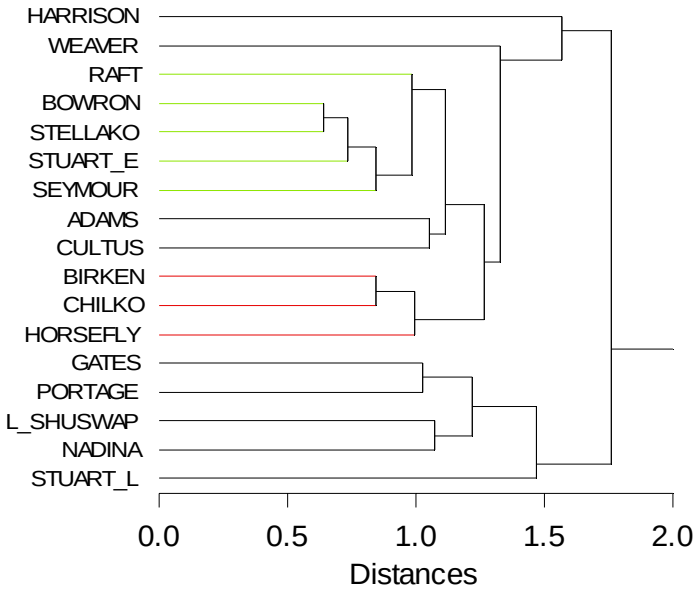

Figure 96: Hierarchical cluster analysis of log(recruits per spawner) of 17 stocks with lengthy production data. Stocks clustered together have more similar histories than stocks not in a cluster. Note that the last stock to be included (Harrison) has the most dissimilar life history. BIRKEN= Birkenhead R. population.

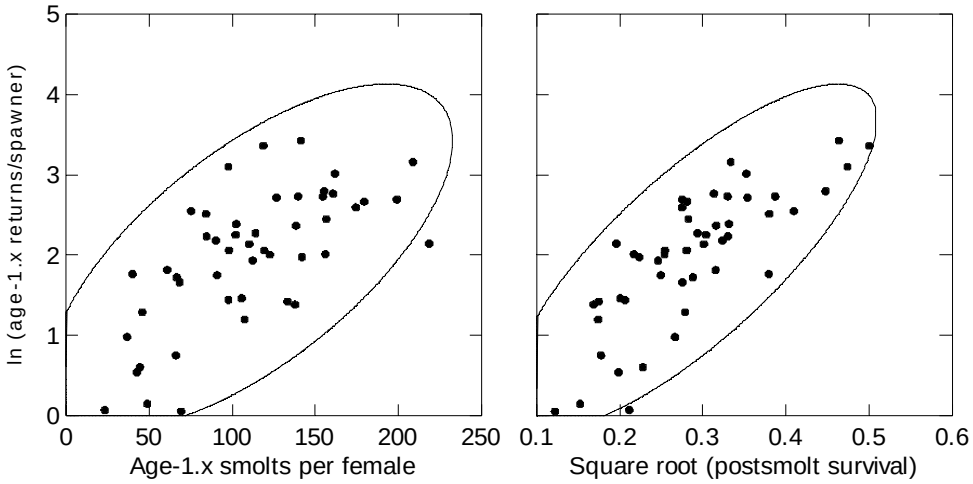

Figure 97: (Left) Logarithm of returns of age-1.x sockeye salmon per effective female spawner versus freshwater survival (ratio of numbers of age-1.x smolts per effective female spawner), and (right) ordinate as in (left) versus smolt-to-adult survival (√ transformed) of age-1.x sockeye salmon from Chilko Lake. From the ordinate alone, as is the case in many Fraser River sockeye salmon populations, the source of variation in total survival (fresh or salt water) cannot be determined.

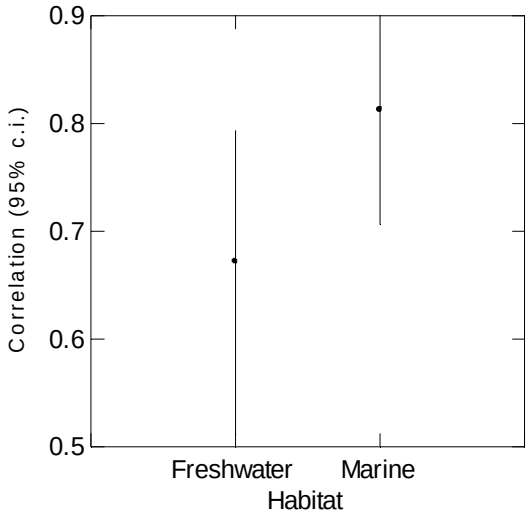

Figure 98: Dots indicate the average of bootstrapped correlations and the whiskers indicate their 95% confidence intervals, of total survival and freshwater survival, and total survival and marine survival, of Chilko Lake age-1.x sockeye salmon.

For the remaining populations where smolt abundance is not observed, the relative contributions of freshwater and marine effects on survival can only be assumed. Fry to adult survival tends to favour a marine origin for the decline[213]. But the inclination is to presume that recent changes in productivity

are largely of marine origin because these populations share a common ocean but not a common lake. These populations also share a common means of egress to the sea but this life history stage is rarely examined in detail because it is such a short period of their lives. Although they may rear in freshwater in different locations, some are exposed to similar effects of climate, particularly in winter[214]. These points have been raised, not to argue that a freshwater cause for the decline should be sought, but to highlight what can be known with certainty.

7.2.2 Gradual versus abrupt decline

The Key Question posed above by the Cohen Commission describes the decline in productivity as a 15-year gradual decline. This point deserves closer scrutiny because trend lines are designed to smooth discontinuous patterns of variation. Applying trend lines to total survival data such as is shown in Figure 99 leaves an impression of gradual downward change in total survival, accelerated recently by low values for the 2003 and the (incomplete) 2005 brood years. As the purpose of the trend line is to smooth over year to year variation and reveal longer term change, rapid and persistent changes in total survival from year to year are blurred by the smoother, and also because smolts of different ocean entry years from the same cohort are pooled when total survival is considered as the variable of interest.

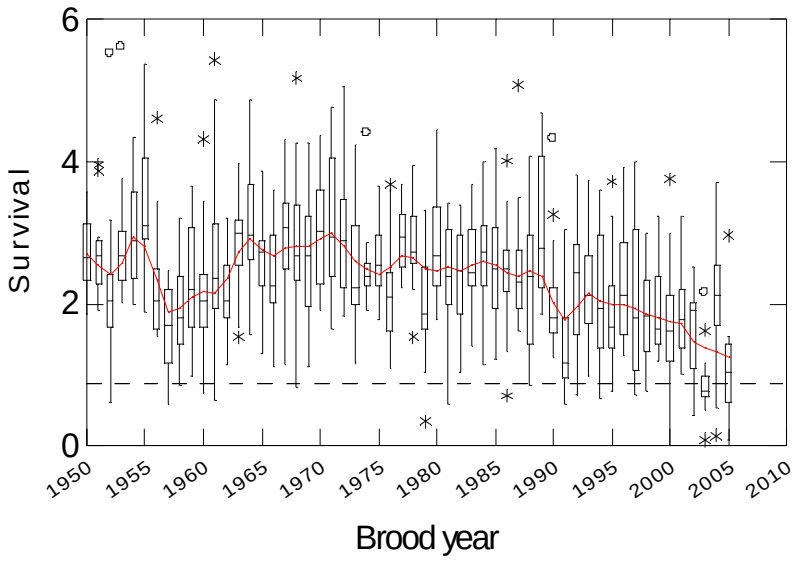

Figure 99: Box and whisker plot indicating brood year by brood year variation in total survival among 16 major Fraser River sockeye salmon stocks (Harrison excluded). The short horizontal lines in each box are median values. The red line is a loess smoother indicating a long-term trend. Data for the 2005 brood year were augmented with anticipated returns of older fish in 2010 (calculated from mean values observed from the 1983–2004 brood year). Survival of the 2005 brood year based on returns observed to 2009 is indicated by the dashed horizontal line.

An abrupt decline in median productivity appeared beginning with the 1992 ocean entry year of the age-1.x ecotype (Figure 99). No other year in the previous three decades was as low as this. It was the onset of a relatively persistent period of lower average survival of Fraser River sockeye salmon that continued through the 2007 ocean entry year. The 2005 and 2007 ocean entry years, and perhaps 1993 as well, are anomalous in the entire record. Keep in mind that the 2007 ocean entry year is incomplete and total survival of all ecotypes to date is only estimated.

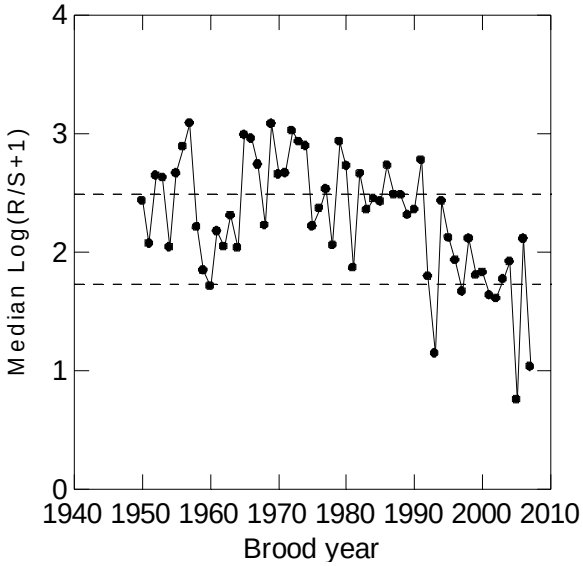

Figure 100: Median total survival of the age-1.x ecotypes of sockeye salmon from 16 major stocks in the Fraser River (Harrison excluded). The 2005 brood year was augmented with an estimate of the expected numbers of age-1.3 fish in 2010 (based on average proportions of these ecotypes). The horizontal lines indicate average values before and after 1992.

Using the data in Figure 100, each year was considered sequentially to determine if it was the year when average productivity declined (Equation 1). The year that provided the best fit (smallest residual sum of squared deviations from a "two mean state" model) was the 1990 brood year (1992 ocean entry year) for age-1.x smolts (Figure 101). A similar result (1992 shift to lower productivity) was obtained with a more sophisticated regime-shift analysis (STARS)[215]. Furthermore, there was no statistically significant linear trend in the median productivity from the 1992 ocean entry year to the present, and none from 1975–1991 ocean entry years, suggesting that the decline was a shift to lower productivity rather than a trend. The STARS analysis also detected a persistent increase in average productivity in 1965 and a decrease in 1975 (Figure 100). There was no equivalently timed change in median productivity of age-2.x smolts. The best division of the age-2.x ecotype time series into periods of higher and lower productivity is the 1985 ocean entry year, although beginning with the 1981 ocean entry year, there was a marked improvement in fit. There was no known corresponding change in oceanic productivity in either of these years.

Equation 1: Formula for goodness of fit; rs_j is the median of ln(R/S + 1) from ocean entry year j across 16 major stocks, rs_1 is the average of rs_j in period 1 (from 1951 to year i-1) and rs_2 is the average of rs_j in period 2 (from ocean entry year i to 2007). The largest change in mean survival occurs at the ocean entry year with the minimum RSS.

$$RSS_i = \sum_{j=1950}^{j-1} \left(rs_j - \overline{rs_1}\right) + \sum_{j=1}^{2007} \left(rs_j - \overline{rs_2}\right), \quad i = 1951, 2007$$

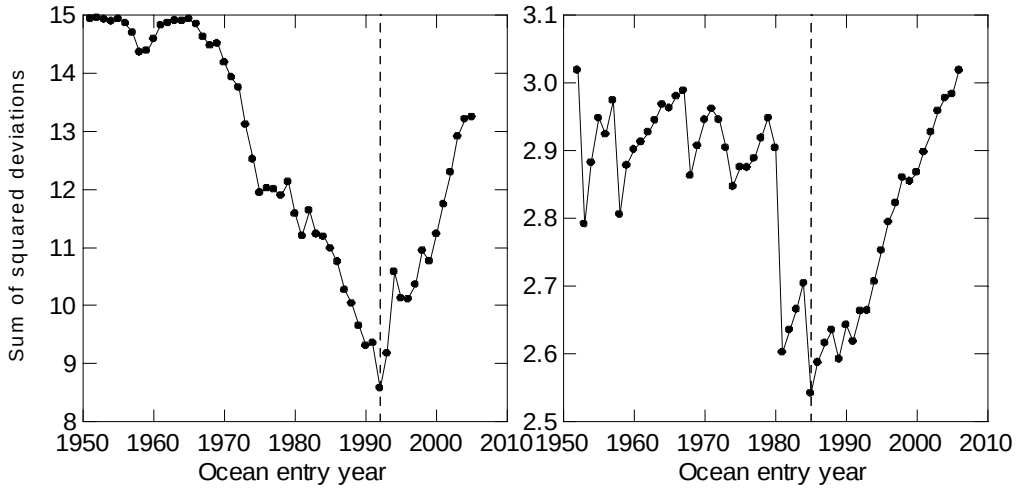

Figure 101: Goodness of fit to a two state productivity model (left panel: age-1.x ecotypes and right panel: age-2.x ecotypes). The minimum value indicates the year of best fit for single step change in productivity. The vertical line indicates that the 1992 ocean entry year is the best year to divide the age-1.x series into two parts and the 1985 ocean entry for the age-2.x series.

Considering the alternative model of a gradual decline in productivity, log (returns per spawner) for each major stock (except Harrison) was considered independently against two hypothetical models. The first model was the "two mean state" with a shift in 1992, described above. The second model was a linear decline from the pre-1992 mean state until 2006. The lower residual sum of squared deviations from these two models (with the same number of parameters) was used to judge which model was a better fit to the data. No attempt was made, give the available time, to determine whether the two models could be distinguished based on the observations.

The temporal pattern of log(returns per spawner) of the age-1.x ecotypes in 12 of the 16 stocks with the longest time series suggests that the decline in productivity that is described above as a "15 year gradual decrease" was a shift in the average (beginning with the 1992 ocean entry year) rather than a trend. Of the four remaining stocks, one (Raft) has no significant change in the mean state and had no trend after 1992. The remaining three (Adams, Bowron, Stellako) indicated that a declining trend from 1992 to 2006 provides a better fit to the data. The change in the average productivity coincides with

the overall decline in average sockeye salmon productivity, which occurred in 1992, that is most evident in populations producing small smolts that border Queen Charlotte Strait/Sound[216]. The cause of the downturn is not known but it appears, to varying degree, in most stocks that use Queen Charlotte Strait/Sound as a postsmolt migration route. The recent finding of a good correlation between chlorophyll concentrations at the northern end of Vancouver Island and Chilko Lake postsmolt survival may serve as a basis for future research. This is a region where seabird productivity, for example, is known to vary from year to year from changes in phenology and the state of the ocean[182].

Table 7.2.2: Comparison of goodness of fits (residual sum of squared deviations) to two simple two-parameter models of productivity (shift in average in 1992 from high to low, versus a linear downward trend after 1992 from the average value for years before 1992). The P(shift) column is the probability of no difference in mean values between the two periods (values > 0.05) are generally considered to be differences in the mean that arose by chance.

Stock	Shift SS	P(shift)	Trend SS	Better Fit (T=trend, S=Shift)
Adams	48.12	0.09	47.06	T
Birkenhead	23.88	0.00	33.50	S
Bowron	26.63	0.02	24.58	T
Chilko	24.56	0.00	26.77	S
Cultus	36.62	0.10	37.49	S
Gates	42.93	0.00	44.52	S
Horsefly	30.21	0.00	30.34	S
Lower Shuswap	72.87	0.00	74.18	S
Nadina	40.66	0.00	41.37	S
Portage	83.14	0.01	84.08	S
Raft	28.58	0.80	28.58	–
Seymour	30.45	0.00	34.69	S
Stellako	17.68	0.00	14.49	T
Early Stuart	16.67	0.00	20.51	S
Late Stuart	63.93	0.00	67.76	S
Weaver	47.93	0.18	50.07	S

The abrupt decline in sockeye salmon productivity which began in 1992 was most apparent in Owikeno Lake and in Long Lake[216] in central B.C. (Figure 102). Evidence of this decline also appear in the Columbia River where adult returns in 1994 (the 1992 ocean entry year), measured at the Bonneville Dam, declined and remained low until the 1998/99 la Niña[217], and in recent returns to Quinault Lake on the West coast of Washington State. Catches of Barkley Sound sockeye salmon declined from significantly above average to below average beginning in 1994 (1992 ocean entry year of the dominant age-1.2 ecotype) although they, too, recovered with the 1998/99 la Niña. The concomitant declines in sockeye salmon productivity from the Columbia River to Queen Charlotte

Sound suggest that the factors which were responsible for initiating a period of lower survival affected a significant fraction of the West coast including Queen Charlotte Sound. A concomitant decline does not appear in Babine Lake sockeye production, but this is not unexpected, as the Skeena River delivers its smolts into a different biogeographic zone[218].

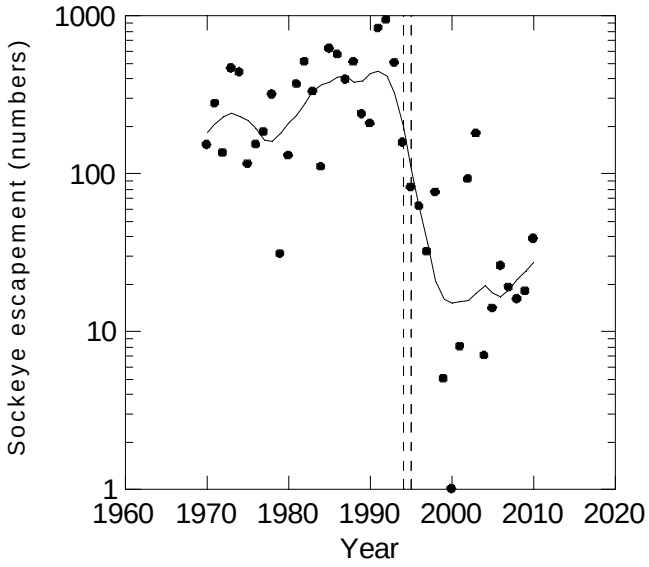

Figure 102: Annual numbers of sockeye salmon migrating upstream at the Docee River fence. Vertical lines indicate the return years of cohorts whose members went to sea in 1992. The trend line is a loess smoother. DFO data source: http://www.pac.dfo-mpo.gc.ca/northcoast/counts/docee/default.htm

Some of these patterns of variability are expressed in ecosystem indicators for the West coast. The Mackas Ecosystem Productivity Index (MEPI)[146] integrates ecological observations (physical, chemical and biological) related to the productivity of the ocean on the Southwest coast of Vancouver Island. According to the MEPI, a warm and unproductive period in the coastal ocean began in 1992 (Figure 95). Extreme values of the MEPI can reflect wholesale changes in the coastal ocean, not simply a change in temperature of the coastal ocean. The replacement of Subarctic copepods, for example, with species of more southerly origin alters the makeup of the food web in ways that are just beginning to be explored. Shifts in species abundance occurred at various trophic levels in 1992 and it coincided with the return, after more than a 40 year absence, of the sardine (*Sardinops sagax*) to the West coast of Vancouver Island[219].

The MEPI returned briefly (1999–2002) to cool and productive but this was not reflected in a marked improvement in marine survival of Fraser River sockeye salmon. Either this reflects a transient connectivity between the MEPI and Fraser River sockeye salmon survival, or it reflects a coincidental association of extremes beginning in 1992. The latter seems less likely because the most positive year of the MEPI (2005) corresponds to the lowest median survival of a cohort (2003) of Fraser River sockeye salmon (Figure 100) and served as a basis for reasonably accurate coast, wide predictions of

returns of many salmonid species and stocks with that particular ocean entry year. The transient mismatches could be a result of variable spatial scales of the dominant forces affecting the MEPI, or of a mismatch between the dates of sampling of the variables that constitute the MEPI and the timing of the seasonal expression of the factor(s) that affect Fraser River sockeye salmon survival.

For the 20th century, the oceanic and atmospheric climates of the North Pacific have been described in terms of regimes; periods of persistence anomalies that shift abruptly among phases[220]. The year 1989 was identified as a time of one of these climate shifts[138, 221] but the common year of decline of Fraser River, Long Lake and Owikeno Lake, and to a lesser degree Columbia River, Quinault Lake , and Barkley Sound sockeye salmon was the 1992 ocean entry year. The extent to which the 1989 climate change and the 1992 sockeye salmon productivity change are interrelated is unknown, but it has been suggested.[222] The coincidence of a shared change in sockeye salmon productivity in 1992 suggests that these stocks were affected by a relatively large-scale coastal influence that had a more persistent effect on stocks using Queen Charlotte Sound and Strait.

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Appendix 1

North Pacific Marine Science Organization (PICES)

PICES is an international, intergovernmental organization that was created by Convention in 1992. The purpose of the Organization is:

- to promote and coordinate marine scientific research in order to advance scientific knowledge of the area concerned and of its living resources, including but not necessarily limited to research with respect to the ocean environment and its interactions with land and atmosphere, its role in and response to global weather and climate change, its flora, fauna and ecosystems, its uses and resources, and impacts upon it from human activities; and
- to promote the collection and exchange of information and data related to marine scientific research in the area concerned.

Scientific leadership in the Organization is the responsibility of its Science Board. Its authority is described in the Rules of Procedure of the Organization as follows:

i. The Science Board shall consist of the Chairmen of the Scientific Committees, Technical Committees, and Advisory Panels of Scientific Programs, together with a Chairman elected by the Science Board from among the nominees for a term of three years. The Chairman shall not concurrently be a Chairman of another group nor be eligible for re-election for successive terms. When the Science Board chairmanship becomes vacant for any reason, the Science Board shall elect a new Chairman at its earliest convenience;
ii. The Vice-Chairman of the Science Board shall be elected from amongst the members of the Science Board for a term of one year and shall be eligible for re-election for a successive term. The Vice-Chairman will normally reside on the opposite side of the Pacific to the Science Board Chairman. The Vice-Chairman shall act as Chairman whenever the Chairman is unable to act;
iii. Should a Contracting Party have no representation on the Science Board via committee or program chairmanship, it may appoint a suitably qualified member;
iv. The Science Board shall:
    a. have general oversight over
        i. the scientific interests of the Council and its scientific work;

ii. the programs of research approved by the Council;
iii. the arrangements for carrying out the Council's scientific work and the programs of research recommended or coordinated by it;
iv. the organization of special scientific meetings.

b. be responsible for advising the Council on all matters mentioned in sub-paragraph (a);
c. provide guidance, as it may deem necessary, to groups under their jurisdiction, as to the performance of their functions;
d. review and make recommendations to the Council concerning the provision of scientific advice to Contracting Parties or other international organizations requesting such advice;
e. consider, at each Annual Meeting of the Science Board, reports from all groups under their jurisdiction and report thereon to the Council with special reference to any expenditures involved;
f. advise the Council of its publication requirements.

v. Scientific Programs shall have a single vote in decisions of the Science Board.

In 1993, the Organization established a procedure to respond to requests for scientific advice made by Member Nations and other organizations. Requests are received by the Executive Secretary and directed to the PICES Chairman. After reviewing the request, the Chairman may bring the request to the Organization's Science Board for consideration. After discussing the request, Science Board may agree to respond to the request. Their response is, generally, to form an *ad hoc* group to draft the Organization's response.

On April 23, 2010, the PICES Science Board discussed the request from the Cohen Commission at its meeting in Sendai, Japan and agreed to take on the project. Dr. Stewart (Skip) McKinnell, Deputy Executive Secretary of PICES, was asked by Science Board to lead the development of the response and to take responsibility for forming the *ad hoc* group and to develop, jointly with the Cohen Commission, the Table of Contents for the PICES response. Internal review of the report was conducted by the PICES Advisory Panel on Status, Outlooks, Forecasts and Engagement prior to approval by the Science Board and the Governing Council of PICES.

Further information is available at http://www.pices.int/about.

Appendix 2

Terminology

Term	Usage
age-class	The *x.y* convention defines x = number of winters in freshwater after hatching, and y = number of winters in saltwater. Each unique combination is an ecotype.
brood year	Year when salmon eggs are laid.
brood year return	See total returns.
ecotype	Distinguishes individuals that spend varying numbers of years in freshwater and saltwater.
effective female	A reduction of the estimated numbers of female spawners due to pre-spawning mortality or incomplete egg deposition.
emergence	Developmental stage when juvenile salmon emerge from their gravel nest.
immature	Older than a postsmolt but will not mature in the current calendar year.
jack	A male anadromous sockeye salmon that matures after one year at sea.
jill	A female anadromous sockeye salmon that matures after one year at sea.
landfall	Latitude where sockeye salmon returning to the Fraser River from the central Gulf of Alaska reach the coast.
life history type	See ecotype
life table	Table of stage-specific survivals of a population.
maturing	A salmon that will migrate to its natal river during a calendar year.
northern diversion rate	Proportion of the total return of Fraser River salmon that enter the Strait of Georgia via Johnstone Strait.
postsmolt	A juvenile salmon that has undergone the physiological changes necessary to live

Term	Usage
	at sea, emigrated from freshwater, in its first calendar year at sea.
productivity	Numbers of returns per effective female spawner, by brood year.
returns	Catch plus escapement, by ecotype. See also total return.
smolt	A juvenile salmon that has undergone the physiological changes necessary to migrate to sea but has yet to reach the sea.
spawner	Males and females that reach the spawning grounds.
total return	A quantity calculated as the sum of the estimated numbers of adult salmon of a population taken in the catch plus the estimate of the number of spawners in that population, computed across all life-history types; sometimes called brood year returns.
total survival	The sum of the numbers of fish from one cohort (brood year) taken in fisheries and the numbers in the escapement, regardless of year of maturation, divided by the number of effective female spawners that gave rise to the cohort.
underyearling	A fish that enters the ocean in its first spring/summer after hatching.

Appendix 3

Average age composition based on brood year returns to 2004

	Ecotype								
Stock	0.1	0.2	0.3	1.1	1.2	1.3	2.1	2.2	2.3
Adams	0.0000	0.0003	0.0026	0.0274	0.9210	0.0474	0.0000	0.0015	0.0000
Birkenhead	0.0000	0.0000	0.0000	0.0672	0.6381	0.2405	0.0091	0.0407	0.0044
Bowron	0.0000	0.0001	0.0001	0.0011	0.8572	0.1405	0.0000	0.0010	0.0000
Chilko	0.0000	0.0000	0.0000	0.0102	0.8792	0.0518	0.0020	0.0553	0.0014
Cultus	0.0000	0.0007	0.0000	0.0257	0.6404	0.0244	0.0002	0.0037	0.0000
Gates	0.0000	0.0000	0.0000	0.1044	0.8220	0.0633	0.0006	0.0098	0.0000
Harrison	0.0016	0.4413	0.5541	0.0011	0.0017	0.0002	0.0000	0.0000	0.0000
Horsefly	0.0000	0.0000	0.0004	0.0037	0.9156	0.0787	0.0000	0.0015	0.0000
L._Shuswap	0.0000	0.0104	0.0012	0.0247	0.7681	0.0562	0.0003	0.1033	0.0000
Nadina	0.0000	0.0000	0.0000	0.0018	0.8766	0.1205	0.0000	0.0010	0.0000
Portage	0.0000	0.0000	0.0000	0.0413	0.9217	0.0263	0.0002	0.0105	0.0001
Raft	0.0000	0.0005	0.0007	0.0024	0.7456	0.2381	0.0000	0.0098	0.0028
Seymour	0.0000	0.0000	0.0000	0.0050	0.9241	0.0466	0.0005	0.0239	0.0000
Stellako	0.0000	0.0000	0.0001	0.0008	0.8501	0.1489	0.0000	0.0001	0.0000
E. Stuart	0.0000	0.0000	0.0000	0.0019	0.9130	0.0821	0.0000	0.0029	0.0001
L. Stuart	0.0000	0.0000	0.0000	0.0037	0.8978	0.0982	0.0000	0.0002	0.0000
Weaver	0.0000	0.0012	0.0007	0.0081	0.8631	0.1232	0.0001	0.0036	0.0000

Appendix 4

Comments on PSC workshop report

The Pacific Salmon Commission (PSC) held a workshop from June 15-17, 2010 to evaluate the cause of declining abundance of Fraser River sockeye salmon. An international panel of 11 scientists considered various hypotheses and brought data to bear on them. The results were consolidated in a report to the PSC that was later made available for information to PICES[213]. Of the 11 hypotheses considered by the panel, #3 - *Oceanographic conditions (physical and biological) inside and/or outside the Strait of Georgia* is most closely aligned with the subject of this report. The key problem for this panel was an observation that 16 of 18 major Fraser River sockeye salmon populations have shown a decrease in productivity over the period of record (since ~1950). They reported that most, but not all, populations have a declining trend in total (generation to generation) survival. The Cohen Commission requested our comments.

►Main Conclusion: The Panel's judgments, summarized in their Table E-1, is that physical and biological conditions inside the Strait of Georgia during the juvenile life stage are very likely the major cause of poor survival of the cohort that returned in 2009.

- First, we note that *very likely* is codified language to describe the likelihood of an outcome. This codified language was used extensively in developing the widely read Intergovernmental Panel on Climate Change's (IPCC) 4th assessment report. The definition of *very likely* in that report is >90% chance of occurrence. Without a close reading of the PSC report, those more familiar with the more widely distributed IPCC report may inadvertently assume greater likelihoods than were intended by the authors.
- We noted that in their Table E-2(3), under "Plausibility and Realism of Proposed Mechanism", concerning the overall decline, "*a lack of detailed knowledge about spatial/temporal patterns of marine migration of juvenile sockeye, phytoplankton, and zooplankton abundance, and salmon mortality make it hard to distinguish between early mortality in Strait of Georgia and later mortality further North.*" This uncertainty is not reflected in their main conclusion, so perhaps its strength arose from hypotheses other than those related to the ocean. Examination of the physical, chemical, and biological data in the Strait of Georgia and, more importantly, extreme climatic events in Queen Charlotte Strait and Sound diminishes the

likelihood of such strong attributions of cause to the Strait of Georgia.

- The smallest and presumably most vulnerable juvenile sockeye salmon that the Fraser River produces (Harrison River) spent the summer of 2007 in the Strait of Georgia and returned in record numbers in 2009 and 2010 (combined). If the Strait of Georgia was the sight of incremental mortality, it must have changed from an extremely unfavourable environment to an extremely favourable environment between June and July, but only after allowing "normal" survival of large, acoustically-tagged smolts from Cultus Lake before the change.

►There is a positive correlation between the abundance of juvenile sockeye (catch per unit effort) in the Strait of Georgia and log(total Fraser SK production) two years later over 1998–2007 (R^2=0.35 with all of the data). Table E-2(3)

- Juvenile sockeye salmon have been caught incidentally in DFO chinook and coho salmon trawl surveys of the Strait of Georgia since 1997. Incidental catches of sockeye salmon have not been reported because they were considered to be too difficult to interpret[210]. As of September 2010, DFO reported that the detailed sockeye salmon data were irretrievable so an independent analysis was not possible for this report.[xix]
- Strait of Georgia sockeye salmon CPUE data have been used to forecast returns of Fraser River sockeye salmon beginning with the 2007 return year, and were reported annually in the DFO State of the Ocean report. Forecast skill has been low. In 2007 and 2008, above average returns were predicted but below average returns occurred. In 2009, below average returns were predicted and observed. High sockeye salmon CPUE in the Strait of Georgia in September was described as a harbinger of low marine survival[210], yet the very high CPUE in September 2007 was matched by very high returns to the Harrison River in 2010 (most spend three years at sea).
- Calculating a correlation between the abundance (CPUE) of juvenile sockeye in the Strait of Georgia and returns two years later demands that only age-1.x and age-2.x juveniles and adults be used in the calculation because underyearlings generally return after three years at sea. If freshwater age, which can often be approximated from juvenile size, was not considered in the calculation, and if the samples contained large fractions of underyearlings (expected in July sampling), then the correlation is a spurious result.
- An R^2 = 35%[99]. , if calculated correctly, would explain the relatively poor performance of forecasts based on Strait of Georgia CPUE, leaving a potential for the other 65% of the variability in total returns to lie beyond the Strait of Georgia. At issue is how much of the abundance of age 1.x and age 2.x ecotypes remain in the Strait of Georgia into July to be taken by the survey and whether it varies from year to year. A plot of annual sockeye salmon CPUE versus annual summer survey start date from 1997 may help to clarify this point. The hypothesis is that later starting dates will result in lower CPUE of age-1.x and age-2.x ecotypes.

►This [Heydon Lake] favourable survival suggests that the unfavourable conditions affecting seaward migration of Fraser sockeye smolts in 2007 existed south of Johnstone Strait.

- Heydon L. is located north of Sayward, B.C. on the mainland side of Johnstone Strait. If Heydon L. sockeye salmon entered the ocean in the same month as other southern populations, and travelled at similar speeds, their northward migration through Queen

xix D. Levy, Cohen Commission, personal communication.

Charlotte Strait/Sound toward the Alaska would have preceded the period of extreme river discharge. With less distance to Alaska, they may be less reliant on productivity timing in Queen Charlotte Sound.

►Eight stocks with additional data on juvenile abundance (fry or smolts), have shown no reductions in freshwater productivity.

- Declining productivity in Chilko Lake, up to the 1999 brood year (2004 return year), was due largely to reduced average freshwater survival. Brood years of the mid-2000s had a period (unexplained, as yet) of remarkably good freshwater survival in Chilko Lake with record smolt abundances emigrating from the lake. The Chilko Lake freshwater time series cannot be characterized as "no reductions in freshwater productivity." For the other populations, it can only be assumed because no smolt counts are undertaken.

►The shared downward trends in total and post-juvenile productivity indicate that the mortality causing declines occurred in habitats shared by the stocks. Table E-2(3)

- While the shared trend suggests a shared habitat for those stocks exhibiting the trend, the appearance of a common trend is insufficient grounds for attributing the cause to the ocean. The scale of the forces that are responsible for the mortality must be taken into account. If it is large, the sockeye salmon inhabiting different locations can be affected by a common cause. The Chilko Lake stock shares the common trend but a large portion of its trend is due to factors operating in freshwater.

►The total productivity (R/EFS) for most Fraser SK is much more highly correlated with post-juvenile (R/juvenile) than with juvenile productivity (juveniles/female).

- In the one system where total freshwater productivity can be distinguished from postsmolt productivity (Chilko), this is a true statement if one considers only the maximum likelihood estimate of the parameter. The correlation with productivity is higher for marine survival but whether or no a strong inference can be made from this measure is less clear.
- A bootstrap program was written to measure the interval estimates of these correlations based on 48 years of data from Chilko Lake. To reduce the complications that arise from pooling smolts of different age, the correlations were computed between log(returns per age-1 smolt) and freshwater survival of age-1 smolts (numbers of age-1 smolts per effective female), and the same versus marine survival of age-1 smolts (age-1.x returns per age-1.x smolts). The marine survival was square root transformed to de-emphasize the influence of very few years of very high survival. Based on 1,000 bootstrap iterations, the average correlation between total survival and freshwater survival was 0.62, and the average correlation between total survival and marine survival was 0.79. However, the 95% confidence intervals on these correlations, computed by bootstrapping, were not significantly different.

►There is a very strong correlation (r^2= 0.87) between algal biomass (Mar 30-Apr 22 avg. chlorophyll a) in QCS and Chilko SK marine survival (1998-2007). However, the mechanisms are not understood.

- The observation of a correlation between chlorophyll concentration and sockeye salmon survival is consistent with Ware and Thomson's[5] study that followed correlations of chlorophyll concentration through zooplankton biomass to resident (non-migratory) fish production. While the exact details of the mechanism may not be fully understood, a

trophic/metabolic mechanism for reduced survival is at least plausible, and one that should not be rejected out of hand given the environmental extremes that occurred in Queen Charlotte Sound/Strait. What is yet to be resolved are the relative contributions of *in situ* production (interannual variation in primary production), phenology (interannual variation in timing of biological production), and advection (interannual variation in the locations of major currents/water masses) in creating the correlation. Each of these has the potential to make Queen Charlotte Sound unsuitable for sockeye salmon in spring. Cassin's auklets breed on Triangle Island, feed at a similar trophic level on similar prey as sockeye salmon, and their reproductive success is affected more by spring timing[185].

►Two notable exceptions to the trends of decreasing productivity [...] are Harrison and Late Shuswap (the famed Adams River sockeye run).

- Harrison River sockeye salmon productivity has, indeed, increased in recent years, but the survival of the 2005 brood year (2006 ocean entry year) from the Harrison River was the lowest on record. Adams River productivity, described as trendless, appears to have the same general productivity pattern as many of the other Fraser River sockeye salmon populations. For the Adams River, the lowest returns per spawner occurred in the 2003 and 2004 brood years. The 2005 brood year was very similar to other values observed since 1992. Based on preliminary data for 2010, the returns to date are typical for a dominant cycle year at average productivity observed before the 1990 brood year. Some of the difference of opinion on the Adams River population trend may have arisen from pooling the data with other populations as an aggregate Late Shuswap stock.

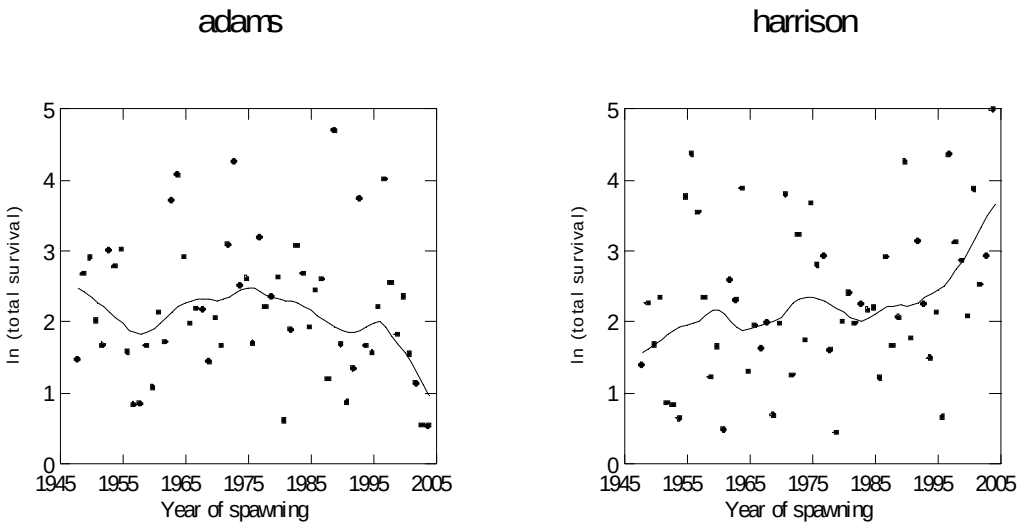

Figure 103: Productivity of Adams River sockeye salmon (left) and Harrison River sockeye salmon (right).

Appendix 5

State of the Science

If you ask a physical oceanographer to describe the current temperature of the Gulf of Alaska, s/he may offer you the perspective from one of several temperature-recording earth-orbiting satellites, or a view of temperatures in the ocean depths from autonomous drifting ocean profilers that relay their daily measurements via satellite, or download the results of the latest cruise, or even take a historical view from century-old lighthouse time series, or a blend of all of the above. If you ask a salmon biologist about the current abundance of sockeye salmon in the Gulf of Alaska, you may not be able to get a reply.

In his book on the ecology of Pacific salmon in the ocean, William G. Pearcy (1992) expressed his view of the state of science and the major unknowns as they were in 1991:

- *We need to know more about the critical time and space scales in the ocean life of salmonids in order to hypothesize mechanisms that determine variations in growth, survival, and migratory behavior;*
- *How do the specific migratory routes of specific stocks of salmonids vary among years?*
- *Are the fish from a given stock found closer together in the ocean than fish from separate or distant stocks, resulting in keener intrastock than interstock competition?*
- *How are the distributions, growth, and survival affected by ocean circulation, both on the large-scale (100-1,000 km), such as the anomalous changes in circulation in the Subarctic Gyre that occurred in the early 1980s, and on the mesoscale (10–100 km), such as the persistent eddy found off Sitka, coastal frontal zones, or offshore banks?*
- *These features and variations in their intensity and location may have important influences on the concentration of salmonid food and predators, on the salmonid migratory routes, and, therefore, on salmonid survival in the coastal and oceanic regions of the North Pacific. Determining what those influences are is a challenging problem for the future.*

W.G. Pearcy (1992)

Some aspects of salmon biology have advanced by orders of magnitude (genetics) but examples of their application to the major questions raised by Pearcy (1992) are, as yet, few. It is no longer

necessary to place a tag in a sockeye salmon in the Gulf of Alaska and await its recovery to understand where it may have originated. It is even possible to understand something of the physiological state of the fish through the genes that are being expressed.[223] Nevertheless, the offshore habitat of Pacific salmon in the Gulf of Alaska has largely been abandoned by researchers, but not for lack of interesting questions that remain to be answered.

And Peterman's (1998) plea after their analysis of sockeye salmon survival:

- *We plea for collection of more extensive data on abundance of early life stages of Pacific salmon. One major reason why it is so difficult to understand the causes of spatial and temporal trends in survival rates, and to deal effectively with their management implications, is the lack of long-term data across numerous stocks on survival rates in different life stages.*

  Peterman et al. (1998)

The observing system for Fraser River sockeye salmon can detect overall productivity changes in many individual populations and on multiple time scales. Many aspects of this observing system provide the basic information to influence decisions that are made in-season to regulate fisheries and implement conservation measures. Fishing is restricted or permitted as abundance in the observing system allows. However, when a change is detected, the observing system will be challenged to find a cause because it does not have this function as part of its design. Observations of juvenile salmon in the ocean are made by individual researchers who have an interest in a particular time and region. The DFO the Strait of Georgia salmon trawl survey, for example, was established to determine the factors affecting chinook and coho salmon survival. As a consequence, the relevance of these surveys to the general biology of Fraser River sockeye salmon is a subject of debate.

The coincidental emergence of juvenile salmon research programs on the continental shelf by various U.S. and Canadian agencies has led to a better understanding of the biology of juvenile salmon at sea[4, 11]. The most promising result of these investigations, however, came from the integration of physical, chemical and biological oceanographic measurements that characterize the marine habitat of juvenile salmon.

There is an interesting dichotomy between the primary interests of scientists who study the cycle of salmon life and the primary observations they make. Most will never have observed the death, by natural causes, of a sockeye salmon in the ocean. Yet for many, the processes that affect the life and death of these animals and their effect on fisheries production are their primary focus. As a consequence, when salmon survive or die at greater than average rates, the scientific community is at a loss to understand why it occurred. The observation system is simply not designed to answer this question.

Some of Canada's international, intergovernmental research on Pacific salmon is coordinated by the North Pacific Anadromous Fish Commission (NPAFC). Its members include Canada, Japan, Republic of Korea, Russian Federation and the United States of America. Since 2002, its member nations have directed their efforts at clarifying the mechanisms of biological response by salmon to the conditions caused by climate change in the Bering Sea[224]. Canadian salmon of Yukon River origin rear in the Bering Sea but Fraser River sockeye salmon are not (yet) known to frequent the Bering Sea in large numbers and Canada has very limited salmon research activities in that region.

The over-arching questions for long-term research and monitoring for the NPAFC will address:

1. What are the current status and trends in marine production of anadromous stocks, and how are these trends related to population structure (spatial and temporal) and diversity of anadromous stocks in marine ecosystems of the North Pacific?
2. How will climate and climate change affect anadromous stocks, ecologically related species, and their North Pacific marine ecosystems?

Canada's contribution to research on Pacific salmon on the high seas (the continental shelf) was described recently[225] in the following:

Research topic	**Season**
Continue collection of biological information on Pacific salmon	All year
Describe ambient oceanographic conditions	All year
Quantify the biomass of zooplankton and describe the zooplankton species community composition	All year
Examination of trends in diet of all five species of Pacific salmon diet	Summer and fall
Examine growth and condition of juvenile Pacific salmon in relation to climate indices	Summer and fall
Determine causes for early marine mortality of juvenile coho and chinook salmon	Spring, summer and fall
Stock identification using DNA analysis and acoustic tag studies	Spring, summer and fall

Last word

"*When it comes to sockeye salmon, don't move too quickly to generalize!*"

K. Groot, 2010

Appendix 6

Reviewers' Comments

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Note to Reader

Except for the report from the North Pacific Marine Science Organization (PICES), Cohen Commission Technical Reports were prepared according to the following schedule:

1. Project initiation meeting to refine the scope and approach to the research (within 2 weeks of the contract date);
2. Preparation of a Progress Report (Nov. 1, 2010);
3. Participation in a Scientific Workshop to present and discuss research results (Nov. 30 – Dec. 1, 2010);
4. Preparation of a Draft Final Report (Dec. 15, 2010);
5. Review of the Draft Final Report by 3 external peer reviewers (Dec. 15, 2010 – Jan. 15, 2011); and,
6. Revision of the Final Report (completion date of Feb. 7, 2011).

The PICES report to the Cohen Commission was a project authorized by its Science Board, a group of international scientists from PICES Member Countries that is responsible for general oversight of the scientific activities of PICES. The development of the report preceded that of the other Cohen Commission projects to accommodate the availability of PICES staff and to allow sufficient time for review, revision, and approval within PICES before being released to the Cohen Commission.

Prior to its release, the report was peer-reviewed within PICES by 5 scientists: two not normally associated with PICES but with strong backgrounds in salmon biology (Dr. Gregory Ruggerone, Natural Resources Consultants, Seattle, Washington and Dr. Masaaki Fukuwaka, Hokkaiko National Fisheries Research Institute, Japan), and three PICES scientists (Prof. Michael Dagg, former Chairman of the PICES Biological Oceanography Committee and Professor at Louisiana Universities Marine Consortium, Chauvin, LA; Dr. Michael Foreman, former Chairman of the PICES Physical Oceanography and Climate Committee and Research Scientist at the Institute of Ocean Sciences, Sidney, Canada, and Dr. Phillip Mundy, Vice-Chairman of the PICES Technical Committee on Monitoring and Director of the Auke Bay Laboratories of the U.S. National Atmospheric and Oceanic Administration, Juneau, Alaska). After revision, the major conclusions reached by the authors were presented to and discussed by the Science Board of PICES who approved sending the results to its Governing Council. The

PICES Governing Council subsequently authorized the release of the report to the Cohen Commission.

In accordance with the deadline specified in the contract with PICES, the Final Report was delivered to the Cohen Commission on Dec. 15, 2010, two weeks after presenting the results at the Commission's scientific workshop, but prior to the commencement of the Commission's formal review process. Due to this time lag, it was not feasible to consider making further revisions to the PICES report. Nevertheless, to make the review process of the PICES report consistent with the other Cohen Commission projects, it was sent by the Commission for further review by 3 external experts. Thereafter, PICES authors were given an opportunity to respond to these reviews. The 3 reviews and responses by the authors (in bolded text) follow below. No changes to the PICES Final Report were made in response to comments by the Commission's reviewers.

Report Title: Marine Ecology
Reviewer Name: Dr. Steven J. Cooke
Date: Jan 15 2011

1. Identify the strengths and weaknesses of this report.

The major objective of the report on Marine Ecology was to assemble as comprehensive a summary as was possible of what is known about Fraser River sockeye salmon in the ocean. Moreover, where possible the authors have attempted to determine if and how ocean conditions may have influenced the decline in sockeye returns observed in 2009. The report is very professional in terms of layout and presentation. Moreover, the document has been proofread such that there are very few typos.

The executive summary is exceedingly clear and acknowledges contrasting observations which is helpful for the reader. After going through the document several times I still have some challenges in connecting the rest of the text with the executive summary. I suspect that this is just a matter of the quantity of material provided in the main document which makes it difficult to integrate in ones head! The authors fail to provide a clear suite of recommendations in the executive summary (along with some comments on the state of the science). That deficiency needs to be addressed. Recall that one of the outcomes of the Commission will hopefully be a suite of recommendations related to research and monitoring priorities. The marine realm is certainly an area in need of additional research and more comprehensive monitoring yet a strong case for such efforts is not presented in the executive summary.

Response: A *Statement of Work* formed a part of the contract between the Cohen Commission and PICES. It included a detailed Table of Contents that defined the scope of the report, and the scope did not include the development of recommendations. Presumably, that is the Commissioner's job. Should he wish assistance/advice in developing them, PICES could be approached to provide it.

Overall the document does a good job of integrating biology and oceanography – something essential for this topic.

The authors have conducted a rather exhaustive search of the literature and have included data from a variety of countries and grey literature (of all sorts). Although there is little information on how information was located (I suggest following the model of the Climate Change team re transparency of searches), the impression I get is that it was a thorough review.

Response: Given the report development schedule and the effects of contract delays, there was insufficient time for a rigorous or systematic search of the literature. Nevertheless, the report managed to be relatively comprehensive simply by engaging those who have worked with a subject for a long time.

A strength of this report is that the authors were directed to include (to the extent possible) a contrast between 2009 (low return) and 2010 (bountiful return).

The team has taken care to present operational definitions where needed which reduced ambiguity (e.g., see appendix 2) – NOTE – THIS MAY BE USEFUL FOR ALL COHEN REPORTS...

The context on page 3 and 4 (e.g., that Canada has no platform for observing or studying high seas salmon beyond the continental shelf) is also helpful for the reader.

Pg 4 and 5 – good historical context.

The summaries provided throughout the document are VERY helpful. This is an information-rich document and it would be hard to digest without such summaries.

The primary weakness of the report is that there are large passages of text (and many of the figures) for which no references are provided. Without the ability to link the data/findings/statements back to a source (whether peer-reviewed or not), it is difficult to assess the credibility of the statements. More simply, without references, much of the text has no credibility. What is odd is that there are sections of the paper that are well referenced (with as many as 5 to 10 references for a single statement). There are also sections where there are entire pages or sections without a single reference. This must be addressed in a revision.

Response: Indeed, there are a few sections that lack references where they could have been provided. Some of this apparent shortcoming arose because the report is trying to serve several audiences: the Commissioner, the scientific community, participant, etc.. Several pages of general introduction to sockeye biology at the beginning of the report, for example, were intended for general audiences and were written in relatively simple language. At some point, citing Gilbert (1913) for example, as the origin of the knowledge that Fraser R. sockeye salmon are four years old at maturity is no longer essential, although Gilbert might argue otherwise if he was still alive.

The second reason for a lack of references in some places is that this document could be considered as an original reference. This report was not, and could not have been, entirely based upon a review of previous work because the cause for the Commissioner's concern has not been determined. Where it was possible, original data were re-analyzed in light of what has been learned since their collection and publication, often decades ago. As the *Statement of Work* included two key questions, whose answers were not known, by definition the report contains original research related to those questions. Whether the material is credible or not depends on the number of flaws or errors detected by expert reviewers of this report. Based on the generally favourable reviews received by the Commission's reviewers, few seem to have been found to date.

Another weakness relates to the figure captions. The authors have included many figures but the majority lack proper references re source and fail to provide adequate information in the caption to enable the reader to interpret the figure. Please provide more details for each figure caption such that they stand alone.

The final weakness relates to the fact that the entire document fails to adequately incorporate much

information on the interface between environment and organismal physiology (especially endocrine state) which ultimately influences behaviour (e.g., when migration is initiated). This is particularly lacking for the section on adult homeward migration which fails to emphasize the cues responsible as well as the role of the endocrine system. See Hinch et al.2005 for an overview and key references. Hinch, S.G., S.J. Cooke, M.C. Healey, and A.P. Farrell. 2005. Behavioural physiology of fish migrations: salmon as a model approach. Pages 239-295 in K.A. Solomon, R. W. Wilson and S. Balshine (eds.). Fish Physiology Series, vol. 24, Behaviour and Physiology of Fish. Academic Press. There is also relatively little discussion of how sockeye salmon find their way back to their home watershed (given the marine focus of this paper that would mean to the estuary rather than natal stream).

2. Evaluate the interpretation of the available data, and the validity of any derived conclusions. Overall, does the report represent the best scientific interpretation of the available data?

On pages 6 through 12 the authors fail to provide references to support their various statements. In several instances they discuss population sizes, show figures (e.g., of ocean distribution, etc) yet provide not a single reference aside from a few historical quotes from newspapers. No matter how matter of fact this knowledge may be for some sockeye biologists, without references, there is simply no credibility here.

Pg 39 – top of summary - another obvious interpretation of why so few tags were returned simply relates to the vast number of age x.1 sockeye in the ocean. 28,000 tags must represent a fraction of a percent of total sockeye at sea – I don't find it surprising at all that only 150 were recovered – in fact, that return rate of tags is actually quite remarkable in my opinion.

Page 39 – Re behaviour of immature sockeye on the high seas. The authors make the following statement in the summary (Immature sockeye salmon potentially have no need to maintain a near-surface distribution for orientation during migration so they may not be exposed equally to the floating longline bait) yet never mention this as a possibility in the text above. The summaries should be based on information presented rather than introducing new ideas. On the top of page 43 there is suggestion that these fish are caught more at night which may reflect their position in the water column.

Text on Page 46 and 47 – there is certainly inter and intra-specific variation in thermal tolerances of fish and this is presumably the case for immature sockeye in the ocean.

Section 5.5. – what about telemetry as a means to estimate survival of both outward migrating smolts and homeward migrating adults? There are data on marine survival from a number of studies over the last 8 years that are not well incorporated into the document. For example, check out the following studies, all of which tagged fish in the marine environment. Although the focus of the papers is to some extent on the freshwater phase of migration, many fish failed to make it to the first in-river telemetry station. These marine losses must be discussed. See the following papers – none of which are cited...

Cooperman, M.S., S.G. Hinch, G.T. Crossin, S.J. Cooke, D.A. Patterson, I. Olsson, A. Lotto, D. Welch, J.M. Shrimpton, G. Van Der Kraak, and A.P. Farrell. 2010. Effects of experimental manipulations of salinity and maturation status on the physiological condition and mortality of homing adult sockeye salmon held in a laboratory. Physiological and Biochemical Zoology 83:459-472 – This

is an acoustic telemetry paper and is relevant to timing of river entry and swim speeds.

Crossin, G.T., S.G. Hinch, D.W. Welch, S.J. Cooke, D.A. Patterson, J.A. Hills, Y. Zohar, U. Klenke, M.C. Jacobs, L.B. Pons, P.M. Winchell, and A.P. Farrell. 2009. Physiological profiles of sockeye salmon in the Northeastern Pacific Ocean and the effects of exogenous GnRH and testosterone on rates of homeward migration. Marine and Freshwater Behaviour and Physiology 42:89-108 – This paper revealed that very few fish that were tagged off QCI made it to river entry – why? That is certainly worthy of significant discussion in the report.

Crossin, G.T., S.G. Hinch, S.J. Cooke, M.S. Cooperman, D.A. Patterson, D.W.Welch, K.C. Hanson, I. Olsson, K.K. English, and A.P. Farrell. 2009. Mechanisms influencing the timing and success of reproductive migration in a capital breeding, semelparous fish species: the sockeye salmon. Physiological and Biochemical Zoology 82: 635-652 - Fish were tagged in the ocean and then tracked to river entry and then spawning grounds – the marine component is relevant. Physiological data also came from marine waters. Focus on fish tagged in 2006.

Cooke, S.J., S.G. Hinch, G.T. Crossin, D.A. Patterson, K.K. English, M.C. Healey, J.S. Macdonald, J.M. Shrimpton, J.L. Young, A. Lister, G. Van Der Kraak, and A.P. Farrell. 2008. Physiological correlates of coastal arrival and river entry timing in Late summer Fraser River sockeye salmon (Oncorhynchus nerka). Behavioural Ecology 19: 747-758 - Fish were tagged in the ocean and then tracked to river entry and then spawning grounds – the marine component is relevant. Physiological data also came from marine waters. Focus on late run fish in 2003.

Cooke, S.J., S.G. Hinch, G.T. Crossin, D.A. Patterson, K.K. English, M. C. Healey. J. M. Shrimpton, G. Van der Kraak and A. P. Farrell. 2006. Mechanistic basis of individual mortality in Pacific salmon during spawning migrations. Ecology. 87:1575-1586. Fish were tagged in the ocean and then tracked to river entry and then spawning grounds – the marine component is relevant. Physiological data also came from marine waters.- Focus on summer run fish in 2003.

English, K. K., W. R. Koski, C. Sliwinski, A. Blakley, A.Cass, and J. C. Woodey. 2005. Migration timing and river survival of late-run Fraser River sockeye salmon
estimated using radiotelemetry techniques. Transactions of the American Fisheries Society 134:1342–1365. – Based on data from 2002 – although focus is on in-river survival, fish were tagged in Ocean so some data relevant to your report.

3. Are there additional quantitative or qualitative ways to evaluate the subject area not considered in this report? How could the analysis be improved?

No – I am content with the analyses provided.

4. Are the recommendations provided in this report supportable? Do you have any further recommendations to add?

Page 140 – section 7.1.3 – first sentence - The following statement is problematic for me... "The emigration of 77 million smolts from Chilko Lake and their low returns in 2009 provides the best evidence, from one of the largest sockeye salmon producers in the watershed, that the mortality occurred in the sea, although the number of smolts that survived the 640 km journey downstream to the Strait of Georgia is unknown." How can you say that mortality occurred at sea when it is not

known how many fish survived the downstream migration? Although the authors note that as an issue, it is equally likely that problem was in river – or a combination.

Page 144 – I have problems with the following statement. "...Strait of Georgia was the not the location of mortality of the 2009 returns of age-1.2 sockeye salmon... It would require conjuring a mechanism that keeps one ecotype alive and abundant while killing the rest." First off, please don't use the word "ecotype" stick with the word "population" in this case (I know you define the term in the appendix and it has its place but you are really discussing the Harrison population here). Second, there is significant intra-specific variation with respect to behaviour and physiology (including environmental tolerances, immune function, energy stores, etc). As such, suggesting that one would have to "conjure up" a mechanism to explain differential mortality is in fact very easy to do. These generalizations are dangerous and need to be tempered. As written they imply bias and lack of understanding of intra-specific variation.

The state of the science (Appendix 5) section fails to provide a clear research agenda or research recommendations. This is an important omission and should be addressed. There is a list of knowledge gaps provided by Pearcy (1992) and some comments about what the NPAFC intends to do. However, that is very different than simply providing a list of the critical knowledge gaps. The table identifying Canada's contribution to "high seas" research is largely limited to the continental shelf. That is clearly a limitation and something that should be addressed. There is also a paucity of examples – what would a Cadillac research and monitoring program look like? What is the role of various tools and technologies (e.g., gliders, telemetry, unmanned aircraft, etc). This should be inventive and forward thinking.

5. What information, if any, should be collected in the future to improve our understanding of this subject area?

On page 4 as part of the context for data limitations, the authors note that "...during the period of years of interest to the Commission, there are virtually no observations of Fraser River sockeye salmon during about 75% of their life at sea, and the value of coincidental samples taken during their emigration from the Strait of Georgia is debatable". That statement alone is worth highlighting!

Page 139 – There are other tools beyond archival loggers that can be used to track fish in the open ocean. "Business card tags" can be put on large animals (e.g., salmon sharks or seals) and used as mobile "receivers" to detect salmon tagged with acoustic telemetry tags (See 19.Holland KN, Meyer CG, Dagorn LC (2009) Inter-animal telemetry: results from first deployment of acoustic 'business card' tags. Endangered Species Research. doi:10.3354/esr00226.). In addition, there have also been recent attempts to use gliders (e.g., the Slocum glider) equipped with acoustic telemetry receivers to track fish on the high seas. These tools show much promise in the future and they have the potential to address some of the challenges with using only archival loggers.

Some topics that are not identified in the state of the science document include the role of changing environmental conditions on cues that influence if and when fish begin the maturation process and initiate homeward migration. The state of the science document is focused largely on routine monitoring to evaluate distribution, abundance and size/growth. The mechanisms that underlie patterns in those ecologically-relevant metrics must also be elucidated. Particular focus should include use of endocrine assays/interventions and genomic studies to develop biomarkers. There is also much opportunity for use of tools related to the spatial ecology, energetic and environmental

physiology of wild free-swimming fish in the high seas. There are new tools (see paragraph above) in biologging and biotelemetry that have great potential to revolutionize our understanding of free-swimming fish and their interaction with conspecifics, confamilials, predators, prey, humans and environmental conditions.

6. Please provide any specific comments for the authors.

I don't mind the PICES logo on each page but the small image of the sockeye is very distracting – especially when reading on a computer screen. Please de-clutter the page by deleting that image.

Another nit-picky comment deals with referencing. The lack of authors names and years in the text means that the reader has to constantly flip back and forth to the reference list. This is a scientific report so those sources do matter. I would encourage the authors to revert to the more traditional name/year in text approach rather than a numbering system.

Pg 15 – Toward bottom of page – When (seasonally, time of day) were fry and post smolts determined to be in the top 3m of water? There are other examples such as this in the text where the statements are so general that they are meaningless without caveats/more info. Now – Very bottom of pg 15 – is that text now referring to the studies above? There are different references cited in different places – very confusing.

Fig 7 – Colours not obvious – Which blue? Orange is hard to see.

Pg 21 – First sentence – reference needed.

Fig 11 – Needs more detail related to clustering technique. This is not a stand alone caption as currently presented.

Top of page 29 – odd referencing style – one has to refer to the figure to figure out the reference for the work completed in 1968.

Middle of page 29 – Reference to work by Mike Healey but no actual reference provided. Lack of credibility for all statements provided due to lack of references. In fact, this problem carries through all of the next few pages until this section ends on page 33. There are MANY statements made here that one can't evaluate because there is little information on where the data came from. This section must be referenced properly OR if this is just a bunch of random anecdotes, then it should be stated as such.

Page 34 – better referencing style here – and better descriptions of methods relevant to ones assessment of data quality. I would hazard to guess that this reflects different people writing different sections.

Page 35 – Back to no references – just noting that data was collected aboard a FRB survey. The figure and text below must be referenced.

Figure 17 – Difficult to see – switch to landscape view and make bigger. Also – figure caption and text contains insufficient detail to interpret the figure.

Figure 18 – "From Brett in Hinch et al" – this is an incomplete reference. Add years and provide more detail. If you decide to stick with the numbered referencing, please include those numbers in the figure captions.

Figure 21 – using what fishing technique?

Page 41 – Anonymous quote at top of page is irrelevant – please delete.

Why are there summaries for all of the sections in 3 (immature fish) yet in section 4 they are used sparingly despite that section being more data rich than section 3? The summary on page 67 in weak and does not cover the range of topics that it should.

Fig 35 and 37 – Make figures the size of entire page – otherwise one cannot interpret different symbols.

Start of text under 4.4.1 – the notion that the work was conducted by a specific group does not serve as a reference. Also – are we now talking about the marine phase of homeward migration now? Somewhat unclear. Same with 4.4.2. Start these sections off with a statement about the fact that fish are starting their homeward migrations...

Page 70 – What is meant by "using a more conservative test of hypothesis"? Are you referring to their alpha value? Please clarify.

Section 4.4.2 seems like it should come AFTER section 4.5 – fish first need to make landfall before you discuss details related to migration speed and timing given that most of those data are collected AFTER the fish make landfall.

Fig 45 – Are those analyses generated by the authors of this report? Please clarify – it is hard to tell which are your analyses versus those of others.

Page 76 – See this paper for fish tagged off QCI and tracked to Fraser. Crossin, G.T., S.G. Hinch, D.W. Welch, S.J. Cooke, D.A. Patterson, J.A. Hills, Y. Zohar, U. Klenke, M.C. Jacobs, L.B. Pons, P.M. Winchell, and A.P. Farrell. 2009. Physiological profiles of sockeye salmon in the Northeastern Pacific Ocean and the effects of exogenous GnRH and testosterone on rates of homeward migration. Marine and Freshwater Behaviour and Physiology 42:89-108

Fig 51 – Difficult to read figure – make it much bigger. Could be full width if you move the legend

Section 6.1 – Please integrate new paper: Thomson, R.E., and Roy A.S. Hourston. 2010. A matter of timing: The role of the ocean in the initiation of spawning migration by Late-run Fraser River sockeye salmon. Fisheries Oceanography (in press).

This is a classic paper relevant to the Fraser sockeye that is not cited in the document... Thomson RE. 1981. Oceanography of the British Columbia Coast. Can Spec Publ Fish Aquat Sci. 56.

Report Title: Marine Ecology
Reviewer Name: David Welch
Date: 15 January 2010

1. Identify the strengths and weaknesses of this report.

This is a generally excellent piece of work, and the authors have provided a thorough and extremely clear summary of their work. They should be commended for the first rate scientific quality of the report—particularly given the tight time frame that the authors had to work within. I rate the report as excellent, although I have some minor quibbles over their discussion of the thermal limit work I had done in the 1990s. This can be easily resolved by sitting down with the authors and comparing data sets, and modifying the text as appropriate. These minor issues do not influence the generally high value of the work for the Commission's mandate.

Response: Thank you; we are not planning to address minor comments at this stage but they will be taken into consideration for any future revisions of this work.

I was not provided the Statement of Work for this report, so cannot comment on whether or not all components of the contract have been addressed.

2. Evaluate the interpretation of the available data, and the validity of any derived conclusions. Overall, does the report represent the best scientific interpretation of the available data?

The report summarizes the marine life history of sockeye salmon, and is an excellent complement to the Peterman and Dorner report; the latter provides a broad-scale perspective on the survival patterns of different sockeye stocks using several statistical techniques that analyze the pattern of change in individual stocks and the degree that the patterns of change in productivity; this report focuses more on the events happening in 2007 leading to the 2009 collapse and an assessment of environmental changes that might co-occur and drive the changes in sockeye productivity.

There are some significant differences between the McKinnell et al and Peterman and Dorner reports stemming from the different starting points and types of data that they employ as that they approached the key issues that the Commission must address. I judge both reports as highly credible. It would be valuable (time and budgets permitting) to try to develop a consensus amongst scientific advisors as to the relative likelihood of which of the different conclusions should be considered "best", and which of the differing viewpoints cannot be resolved at present.

Important differences between the McKinnell et al and Peterman and Dorner reports include the following:

McKinnell et al	Peterman and Dorner
Views "decline" in sockeye productivity as step-function (sudden shift in 1992) in 12 of 16 stocks	Classifies substantially fewer stocks as having a sudden (step-function) decline and describes most as "a trend to lower productivity". (I have not attempted to do the full population-specific comparison, as this needs to involve the authors)
Best division of the time series is 1992, and notes	Identifies 1985 as the major change point.

that 1991/92 forwards was a period of *"persistent El Niños".*	
Does not identify Strait of Georgia as the likely geographic site of the productivity problem, and identifies strong correlations with anomalous events in Queen Charlotte Strait (at least for the 2007 out-migration year).	Ditto, but implicates a common effect to as far north as SE Alaska, suggesting the "problem" is not confined to Queen Charlotte Sound. Does not identify a particular cause or issue for the apparently poor 2007 out-bound smolt survival (as I recall).

3. Are there additional quantitative or qualitative ways to evaluate the subject area not considered in this report? How could the analysis be improved?

I would like to see one additional piece of work completed, time and budget permitting, because it would help clarify the relatively minor discrepancies evident between this report and that of McKinnell et al (which is also excellent). These discrepancies principally involve the year at which climate changes occurred in the ocean and apparently changed the production dynamics of the sockeye stocks. There are differences between the two report's estimates as to the year in which the changes are thought to have begun.

Response: We interpret this comment to mean that the year proposed in this report for a significant change in sockeye salmon postsmolt survival at sea differs between what is described in this report and another paper published by McKinnell et al, but we are not certain which "other McKinnell et al. paper" the referee is referring to. If it was McKinnell et al. (2001) on the collapse of Rivers Inlet sockeye salmon run, the ocean entry year (1992) of a decline to a "permanently closed fishery" matches that proposed in this report. Here is a relevant sentence from McKinnell et al. (2001).... "*The final abundance stanza began in 1994 with the returns from the failed 1990 brood year (1992 ocean entry year).*" McKinnell et al. (2001) also contains the sentence "*What is apparent in Smith Inlet is that beginning with the 1990 brood year (1992 ocean entry year), the recruits per spawner has been persistently less that 1...*"

The referee may also be referring to McKinnell (2008), a paper with no "et al." on Fraser R. sockeye productivity. Other authors had published papers describing 1989 as the beginning of a new oceanic regime. Certainly, there was evidence of significant climate change in that year and that motivated its use as a year to divide the productivity time series in McKinnell (2008). The 2008 paper did not ask the question "When did a change occur?", but it should have. What is unresolved yet is the apparent mismatch between a major ocean/climate event in 1989 and the 3 year lag until an effect appeared in the southern sockeye populations. It may have been because the declines were more closely associated with the "persistent el Nino" that began during the winter of 1991/92 (Trenberth & Hoar 1996).

4. Are the recommendations provided in this report supportable? Do you have any further recommendations to add?

1. Yes, but resolution of as many discrepancies as possible between this and the Peterman & Dorner report would be a useful next step. (Perhaps a workshop format).

2. (This next point is really a piece of direction and advice to the Commission which goes beyond the individual reports that have been requested, but it plays into this report). There have been repeated failures within the Fraser River sockeye complex that have had major institutional disruptions for DFO (generally at significant cost to the taxpayer and little positive improvement in effectiveness that I could identify from the reports that I reviewed for the Commission). John Fraser's review was commissioned as a result of the headlines in 2002 & 2004 that "*DFO lost a million Early Stuart sockeye in the river*". Although much disruption occurred internally in the department while a major re-organization occurred in response to the outside criticism, it was never satisfactorily resolved what caused the sockeye problem and, in fact, has been largely forgotten. Then, starting in 1995 or 1996 (the stated year varies) Late-Run stocks came back and began entering the river early. They too began dying in the river before reaching the spawning grounds. DFO never seems to have been able to connect the two events and ask whether they were part and parcel of the same event, continuing a long and troubling trend of focussing on bits & pieces without seeing the bigger picture. Then, of course, the 2009 collapse occurred, precipitating the current Commission of Inquiry, against the backdrop of a 20 year decline in average Fraser River sockeye productivity. Thus the institutional re-organization lives on as the response, but has apparently been ineffectual in actually resolving why the any of the run failures occurred and seems to have been largely forgotten as the department successively shifted its focus from the "*Early Stuart" problem* to the "*Early – Entry*" problem and now to the "*General Run Failure"* of all stocks (save Harrison) in 2009. One of Peterman and Dorner's major contributions is to demonstrate that this decline in productivity was also affecting Fraser River sockeye ***other than the Late-Run stocks,*** such as Chilko. This is an important point because it begs the question of whether the system has simply addressed various symptoms but failed to get to the heart of the matter: *(a)* What has happened? and *(b)* How is it to be addressed?

p.52. "considering why the ratio is >>1.0 when it should be <1.0. One explanation…". A major part of the explanation, not mentioned, is that salmon likely shed externally attached tags; there are excellent biological mechanisms that allow a damaged animal to extrude foreign bodies that (literally) get under their skin. (c.c. the foreign body reaction that is the bane of artificial implants in humans).

5. What information, if any, should be collected in the future to improve our understanding of this subject area?

A fuller understanding of these issues will require direct measurements and rigorous hypothesis testing. I do not believe that the addition of even several more decades of observational data of the form currently available will suffice to resolve the key remaining biological uncertainties that the Commission has been asked to investigate as part of its mandate.

6. Please provide any specific comments for the authors.

Summary #1, p. xi. It is not possible to be as assertive as the authors state: "When all returns of the 2005 brood year are eventually counted in 2010 and 2011, the lowest median total survival of Fraser River sockeye salmon in contemporary records is the 2003 brood year, not the 2005 brood year." We don't know what 2011 will bring, so re-state to say "very likely".

p. xii "Oceanic conditions with a strong potential to cause incremental sockeye salmon mortality" I am not certain of the intended meaning; re-word.

p. xii "A Fisheries and Ocean Canada (DFO) surveys in late June 2007 (and other years) across southern

Queen Charlotte Sound, east of Triangle Island, recorded…" Re-word: → "A Fisheries and Ocean Canada (DFO) survey in late June 2007 across southern Queen Charlotte Sound, east of Triangle Island, recorded…"

p. xiii (#11). "was the sight of…" → "was the site of…"

p. xiii (#11) As the authors enumerate here, there are multiple reasons why the Strait of Georgia is not likely to be the site where the poor mortality determining the 2009 adult return occurred. This is a striking difference from the DFO submissions to the PSC report of June 2010, and really raises the question why the DFO staff were not able to identify and present the same list and instead argued that the site of the problem was likely in the Strait of Georgia—the exact opposite conclusion.

p. xiv (#4). "The appearance of relatively large numbers of jacks in 2009 in the seine test fisheries suggests that the abundance of the dominant cohort that returned in 2010 was determined before July of 2009." This statement is logically inconsistent with the preceding arguments that the source of the failure occurred outside the Strait of Georgia, as the 2007 smolts would have been inside the Strait of Georgia in May and June. Reconcile.

p. 5 "Surveys to test a thermal limit hypothesis to describe the oceanic range of salmon in the Gulf of Alaska began in 1995[9]." In fact, these surveys started in 1990; cite the following as the source for this date: Welch, D. W., Chigirinsky, A. I., & Ishida, Y. (1995). Upper thermal limits on the oceanic distribution of Pacific salmon (Oncorhynchus spp.) in the spring. Canadian Journal of Fisheries and Aquatic Sciences, 52, 489-503.

p. 10 "The mechanisms underlying this capability are not well known, except that learning of the characteristics of the goal is involved". A quibble, perhaps, but I doubt this—the smolts out-migrate without any adults to teach them the way, and they often (at least prior to 1977) returned to the Strait of Georgia using the migration pathway not used on the outbound migration. This argues for a genetic basis with some adaptive plasticity, not "learning".

p. 17 To avoid confusion, rephrase "..the proportion… was 0.42" with "..the percentage … was 42%". (Some readers may think you mean 0.42% otherwise).

p. 18 Reference 49. The "personal communication" can now be replaced with a draft written report: Clark, T. D., Hinch, S. G., Rechisky, E. L., Riddell, B. E., & Welch, D. W. (2011). River and coastal ocean survival and movements of Chilko Lake sockeye salmon smolts: findings from the 2010 acoustic telemetry study. Pacific Salmon Foundation. 6 pages. (See Brian Riddell for a copy; it should likely be made a formal PSF document so that it can be cited better).

p. 30 "because the smaller individuals are dying faster rate than the larger ones". Grammar.

p. 31 "The first trans-Pacific winter survey for Pacific salmon was conducted by the Fisheries Agency of Japan only as recently as 199668". Incorrect—1992. I was on it (and lost 17 lbs). The data was used in the Welch et al 1998 sockeye thermal limits paper and the track line was shown on one of the figures, but it was not cited by name in the text (but is listed in the database).

p. 45. "Welch et al.92 established the 12°C isotherm in July as a thermal limit to Pacific salmon distribution." This statement is correct only for sockeye—we did not present data for other salmon species in this paper.

Appendix 6
Reviewers' Comments

p. 45 "Sockeye catches in July 1997 were more abundant at temperatures greater than the thermal limit (Figure 27)" Correct, but lacks context—we never said that the sockeye could not violate the thermal limits when they were migrating back in to spawn… and they clearly would have to in order to get back to BC waters because sea temperatures are well above 12C. July is the month sockeye are migrating back inshore to BC, so this method needs to discriminate between maturing and immature sockeye. (Also note that the temperature isotherms angle sharply up to the NE as they approach the BC coast, following the flow). Note to, in your discussion on p. 69, that your own summary of the relationship between return timing of Fraser R sockeye and SSTs indicates that for 75 years they return later in warm years—which suggests that they start from farther west even if they do migrate across the warmer waters of the Gulf of Alaska.

p. 45. "During the latter half of the 1950s and in the 1960s, the Fisheries Research Board of Canada's North Pacific Survey conducted high seas fishing with gillnets and longlines throughout the Gulf of Alaska. Primary fishing stations were 50°N 155°W, 55°N 155°W, 50°N 145°W, 55°N 145°W, 58°N 145°W, 50°N 135°W, and 55°N 135°W." (also related comment in the summary on p. 49). These should have been included in the Welch et al (1998) analysis, as we included all data that we could find back to the mid-1950s, and thus should have been included in the scatter plots. I suggest that we sit down and sort this out before the authors finalize their report—our paper was intended to discuss the offshore distribution of immature sockeye, and not an explanation of the distributional limits of maturing adults (since we know they routinely exceed these thermal limits in freshwater, and BC/Washington sockeye must cross the 12C isotherm (shown in your Fig. 29) every year they return to the coast.).

p. 46. "Rand85 argued that the reduced abundance of sockeye salmon along the southern periphery of the Gulf of Alaska was equally likely to be explained by a sharp reduction in growth potential rather than a behavioural response to SST proposed by Welch et al.91." What can I say? I think Pete didn't read our paper very carefully. From the Welch et al (1998) abstract: "The sharpness of the edge, the different temperatures that define the position of the edge in different months of the year, and the subtle variations in temperature with area or decade for a given month probably all occur because temperature-dependent metabolic rates exceed energy intake from feeding over large regions of otherwise acceptable habitat in the North Pacific".

p. 48 "…these models suggest that, on average, SSTs <12°C will not be a significant part of the Gulf of Alaska at twice the late 20th century CO2 concentrations (Figure 31)." Replace "twice" by "double" to clarify meaning.

p. 48-49. "none of these models yields a northward shift of the 12°C SST isotherm as extreme as was reported by Welch et al.92; see Figure 26" How about "as was reported by Welch et al.92 using the IPCC models available at the time of his analysis" (i.e., please don't shoot the messenger for not foretelling what the next generation of models would bring!! Also, you might point out to the reader that the newer generation of global warming models still show a very sharp reduction in the area of the GOA that is <12C (Fig. 31 contrasted with Fig 29).

p. 49 "Achieving a cooler temperature by vertical movement requires only a few metres of movement…" The summer thermocline is 70 meters down, so "a few meters" is misleading… and my thinking at the time was that (a) electronic tagging did (and still does) show sockeye staying above the thermocline and (b) that there wasn't any evidence for routine vertical migration in the offshore that would get them below the thermocline (and there still isn't from all the more modern electronic tagging studies). Your own review of the vertical distribution of sockeye based on more recent DST studies, a few pages on (p. 65), still reports the same observation of strongly surface oriented behaviour.

p. 82 Six of 40 tagged fish is 15%, not "14.6%".

p. 86 "because it was more than fivefold greater than the next highest value (1997 brood year)…" I think you mean 1998 brood year.

p. 86 "because the dominant populations that made up the return in 2001 do not have populations with significant numbers of jacks." Which populations are they? Specify.

p. 87 Same comment for last sentence in Summary.

p. 104. "Stations in the Strait of Georgia did not exhibit this anomaly pattern (Figure 59)." I find it striking that the DFO submissions to the PSC focused on the need to study the Strait of Georgia, whereas both the McKinnnell et al and Peterman & Dorner reports place the likely source of the problem beyond the Strait of Georgia. I feel it is appropriate to ask why the DFO submissions tended to ignore the residence of Harrison sockeye in the SOG (and their increasingly high survival over time), the higher survival of Sakinaw L sockeye in the Strait of Georgia than for those who leave (Wood et al, In Press), and the need to correct the July survey data for timing of the surveys. I think it is appropriate for the Cohen Commission staff to ask if this blinkered mind set had more to do with wanting to study something relatively easy and close at hand (the Strait of Georgia) and wanting the problem to be in the Strait of Georgia so that they would not have to deal with the possibility of migration past the fish farms.

p. 108. "July 2007 had either the highest average southeasterly flow in the 63 year time series". Intended meaning?

p. 122-23. This section on the ARGOS data needs to reflect the fact that the ARGOS profiles are for the offshore—not the shelf. (The floats rarely come up onto the shelf). It is unclear to me whether this section has any relevance, since the authors are computing stability measures for the offshore, while the smolts are on the shelf. Clarify, please.

p. 124 "The dominant spatial pattern has water column stability lowest in the blocks adjacent to the North American coast and deepest in the block of longitude farthest from the coast." But does the offshore properties necessarily reflect the processes on the shelf, where the smolts are?

p. 125 "Both the 2007 and 2008 smolt years of Fraser River sockeye salmon were in the Gulf of Alaska at this time" Not necessarily the 2008 smolts—we don't understand when they go offshore.

p. 128 "Summary – The seasonal peak in zooplankton biomass in 2008 had not developed as late since the 1970s when they occurred commonly." Fix wording.

Fig. 91 (P. 129). I count more bars than years on this graph—it is very hard to pick off the correct years, so consider labeling some of the key bars with the appropriate years.

p. 131 "July is the month when they emerge onto the continental shelf". Not June? (Same point for summary box on p. 132).

p. 133. "Whether a fish experiences what happens at a station depends on the de-correlation scale of the oceanic phenomenon of interest." Perhaps this is more simply described as by saying that we don't know if different populations have the same behaviour or the same exposure to the measurements that we make!

p. 137 "Surveys conducted in the Gulf of Alaska during the 1950 and 1960s by the Fisheries Research

Board of Canada were never repeated after the Board was disbanded." Not quite correct—I conducted some, but they were neither as extensive nor did they have the same focus.

p. 138-9 I am not certain that the statement "variation in returns per spawner appears to be almost equally shared by freshwater and marine (postsmolt) effects (Figure 97). Bootstrapping each of these comparisons separately indicated that the correlations in the two panels of Figure 97 are not significantly different" I am not completely convinced; the correlation with marine survival is some 20% higher than with freshwater, and the individual 95% confidence intervals in Fig 97 do not overlap. The correct way to form the bootstrap test is to generate the empirical distribution of differences in the two sets of correlations, computed pair-wise, and then ask whether the null hypothesis of $\rho=0$ is included in the empirical distribution of the differences.

P. 140 **"Gradual vs Abrupt Decline"**. I think the analysis here is a bit mis-leading for the average man on the street, who is interested in the demise of Fraser River sockeye. It is clear that the ***average*** has been declining; focusing on individual populations to some degree muddies the water because there can be complex patterns for the individual populations while the average is still going down. Perhaps a more accurate way to analyze the survival pattern shown in Fig. 99 might be to weight the stock-specific survivals each year by average population size, since this reflects what the productivity of the fishable aggregate is.

Fig. 100. The key years have to be labeled on this plot—it is almost impossible to visually sort out which years are which otherwise.

Report Title: Marine Ecology
Reviewer Name: Alan Martin
Date: January 9th 2011

1. Identify the strengths and weaknesses of this report.

The report is well structured and written; it has historical quotes that provide key perspectives on the progress that has been made in sockeye research. The summary sections for the chapters provide key conclusions about the topics.

The strength of the report is that it contains a comprehensive historical summary about Fraser River Sockeye in the Pacific Ocean. The report describes the general biology of the sockeye salmon. It then focuses on the marine phases: (1) post smolt migration through the Strait of Georgia and the continental shelf, (2) distribution behaviour feeding and growth beyond the continental margin and (3) maturation and migration of adults back to the natal rivers. Variations in survival in the ocean are also examined .This section is followed by a description of the oceanography and climate of the Strait of Georgia, continental shelf and the Gulf of Alaska. The report builds on this foundation and discusses two major issues: the cause of low returns in 2009 and gradual decline in marine productivity or change in distribution of sockeye.

The report summary provides a compelling narrative explaining how the low returns to the Fraser River in 2009 may be related to ocean conditions in the Queen Charlotte Sound that could have reduced the survival of Fraser sockeye smolts entering the ocean in 2007. Evidence and arguments regarding the high returns of 2010 are also presented.

The report provides statistical analysis that the shifts in productivity were sudden and not gradual for 12 of the 16 stocks that occurred in 1992. It did not provide evidence as to what caused the shift in the marine environment. The very low returns in three years from 2007 – 2009 were likely due to low marine survival in 2007, very low parent abundance for 2008, and anomalous summer conditions and climate in 2009.

The appendices are informative, particularly the comments on the PSC workshop report.
Notable is the identification of conditions within the Strait of Georgia during the juvenile life stage that could very likely be the major cause of poor survival while the authors point to the extreme climatic conditions that reduced the likelihood of such strong attributions to the area.

Recommendations on approaches to distinguish between mortality in the Strait of Georgia and later mortality further north would be instructive in the fish farm sea lice issue. Application of new technologies including genetics need to be applied to the ocean distribution and survival of sockeye generally.

Appendix 5: The State of Science is particularly relevant, particularly the statement, "That when change is detected the observing system will be challenged to find a cause for this function as part of the design." Recommendations of how to address this point would be instructive.

Response: Comments regarding the lack of recommendations appear with Dr. Cooke's review, above.

2. Evaluate the interpretation of the available data, and the validity of any derived conclusions. Overall, does the report represent the best scientific interpretation of the available data?

The interpretation of the available data and the conclusions are valid. The authors do note that in many cases the data for distribution of sockeye in the marine environment are poor and that the evidence required to detect changes between ocean conditions and marine survival is difficult to assess between areas and years. As many of the historical quotes attest, new approaches and information may radically change scientific interpretation. More research into the distribution of salmon and ocean conditions is required as the assumptions used in current climate change models based on surface sea temperatures are not accurate.

3. Are there additional quantitative or qualitative ways to evaluate the subject area not considered in this report? How could the analysis be improved?

The scope of the report is comprehensive. Relevant information is well analysed. The emphasis that should be pursued in making recommendations should be forward looking to improve study designs so that better quantitative or qualitative approaches for the marine environment can be conducted.

4. Are the recommendations provided in this report supportable? Do you have any further recommendations to add?

Recommendations on approaches to distinguish between mortality in the Strait of Georgia and later mortality further north would be instructive in the sea lice debate as well as the issue of ocean survival generally.

Appendix 5: The State of Science is relevant, particularly the statement, "That when change is detected the observing system will be challenged to find a cause for this function as part of the design." Recommendations of how to address this point are particularly relevant to DFO programs.

5. What information, if any, should be collected in the future to improve our understanding of this subject area?

I think a better question would be, if we have a better understanding of Marine Ecology and is there anything that can be done about it to improve sockeye survival other than varying harvest rates and influencing freshwater productivity. Does the stocking of other species of salmon, including salmon farms, influence the survival of sockeye and to what extent?

6. Please provide any specific comments for the authors.

none

References used in response

McKinnell et al. 2001. The demise of Owikeno Lake sockeye salmon. N. Am. J. Fish. Mgmt. 21: 774-791.

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