EXECUTIVE SUMMARY:

Project 4: The Decline of Fraser River Sockeye Salmon Oncorhynchus nerka (Steller, 1743) in Relation to Marine Ecology

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 (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

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

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 postsmolt survival, suggesting that some fraction of

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

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

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.

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 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 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.

[i] Rensel, J.E., Nicola, H., Tynan, T.M. 2010. Fraser river sockeye salmon marine survival decline and harmful blooms of *Heterosigma akashiwo*. Harmful Algae 10: 98–11