Atmospheric and Oceanic Extrema in 2015 and 2016 and their Effect on North American Salmon

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Pacific Salmon Commission
Technical Report No. 37

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For

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and their Effect on North American Salmon

Part One:
Identification of extrema

Part Two:
Analysis of extrema and recommendations

Part One

Atmospheric and Oceanic Extrema in 2015 and 2016 and their Effect on North American Salmon; Identification of extrema

1. Highlights

1.1 Approach

One of the major findings of the 2010 PICES report on the state of marine ecosystems of the North Pacific was a trend toward increasing variability (McKinnell & Dagg 2010) compared to what had been reported during the five year period prior to that (PICES 2005). If an update was to be written now, the same observation would likely be made. Since 2013, environmental variability has been ratcheted up another notch, with what appears to be variable consequences for North American Pacific salmon. The present report focuses on environmental and biological extrema of 2015 (and 2016 where data are available) in the salmosphere[1]. In most cases, new indices of environmental variability were developed in order to focus on the environmental variability occurring within the salmosphere, or a portion thereof. This section entitled "Highlights" provides a brief written description of what was found when 2015 and 2016 years were compared with available historical records. Atmospheric, oceanic, and biological properties that did not reach extreme values are not included in the highlights but are discussed occasionally.

1.2 Environmental extrema

1.2.1 Air Temperature

The focus of recent analyses of environmental anomalies in the ocean has generally been on the development and duration of sea surface temperature anomalies (SSTa), a.k.a. The Blob, but the development of warm SST was preceded by warmer air temperatures in the salmosphere. There was an abrupt increase in surface air temperatures (SAT) in the salmosphere between May and June of 2013. Principal component analysis of SAT anomalies (SATa) found, not unexpectedly, that the dominant mode of monthly average air temperature variability in the North Pacific salmosphere was closely associated with variation in the Pacific Decadal Oscillation with maximum correspondence ($r = 0.77$) occurring in May. The only extremum recently in SATa-PC1 (since 1948) occurred in April 2016. On the other hand, the subdominant mode (SATa-PC2) had positive extrema in February and October 2015, and also in July and August 2016.

1.2.2 Sea Temperature

a) Surface - There is no precedent in the historical instrumental record of observations of the magnitude and persistence of high sea surface temperatures (SST) in the salmosphere. The abrupt increase in SAT that occurred in June of 2013 and was followed by an abrupt shift in SST during the last two weeks of July of 2013. Apart from a brief cooling in the fall of 2013, SST anomalies (SSTa) have generally exceeded +1 s.d. through to the writing of this report. The maximum extremum observed during this period occurred in September 2014.

b) Subsurface - Salmon do not live at the very surface of the ocean where the satellites are measuring SST. Their habitat is beneath the surface where the uppermost measurements by Project Argo profiling floats are typically recorded (4-5 m). Because they are so few, a relatively coarse grid is required to accumulate monthly spatial statistics. Using a 2° latitude by 5° longitude grid, there are about 7 observations per grid point per year, from which means and anomalies can be computed from 2003. The most extreme anomalies (> ±4°C) at 5 m depth in the eastern salmosphere (eastward of 180° longitude) occurred at its southern fringe (negative) and near the Aleutian archipelago (positive). All of the most extreme

1 The current and future domain of *Oncorhynchus* and *Salmo* in the northern hemisphere.

temperature anomalies were south of 49° latitude.

c) Coastal temperature (high resolution) - A similar analysis was conducted using higher resolution data (daily, ¼° grid) on the continental shelf (< 1000 m) since 1981. The dominant pattern (PC1) is coastwide positive covariation (PC1) throughout the entire Gulf of Alaska. The most extreme of the positive PC1 scores on the shelf occurred in 2016 rather than in 2015. Strong coastal anomalies are typical for an el Niño (McKinnell & Crawford 2007). The three highest positive PC1 scores (>3.6 s.d.) occurred over a 3-day period, May 14-16, 2016. The next 6 highest scores occurred in 2004 and in 2005. In 2015, the rank of the strongest positive score that year occurred on July 12 and it was 19st in the entire record. The strongest positive score in 2014 (50^{th} highest) occurred on December 27. The contrast between pre-2014 average SST and 2014-2016 average SST on the continental shelf is not as great in offshore waters. There is little to no evidence of an overall linear trend in PC1 prior to 2014. PC1 is significantly correlated with survival of Chilko Lake sockeye salmon postsmolts; colder years are associated with higher survival. It has not been cold lately. Daily data collected at Kains Island (NW Vancouver Island) indicated that 2015 was the spicest (warm-salty) year on record (since 1934).

1.2.3 Sea Level Pressure (SLP)

Due to an atmospheric teleconnection, there is a close correspondence between SLP in the western tropical Pacific in winter and air and sea temperatures along the North American coast in the following months. SLP at Darwin, Australia (the western pole of the Southern Oscillation Index) had the highest average January SLP in 2016, in a record that dates back to the 19th century. SLP extrema were found across the entire salmosphere in the North Pacific during January and February of 2016. Although strong (negative) pressure anomalies in the Subarctic are a regular feature of major el Niños, many of the anomalies that occurred in 2016 were extrema. An Aleutian Low index, restricted to the salmosphere was developed and 2016 was only the 3^{rd} strongest in the record, behind 1983 and 1998.

1.2.4 Nutrients

At all stations along Line-P from the west coast to the middle of the Gulf of Alaska, the winter nutrient supply in 2015 was the lowest observed by DFO scientists in the past seven years.

1.2.5 Chlorophyll

a) Offshore - the most noteworthy feature of the record from 2003 was the extreme timing (late) of the fall bloom in 2016.

b) Shelf - the late timing of the fall bloom in 2016 was an extremum.

c) Coastal - the late timing of the fall bloom in 2016 was an extremum.

1.2.6 Zooplankton

a) Offshore - in the eastern Gulf of Alaska, there were no extrema of abundance, biomass, or average size of zooplankton in 2015 measured by the Continuous Plankton Recorder (CPR). This is a standard sampling device that is towed behind commercial ships as they transit the World Oceans including the North Pacific since the late 1990s. CPR data for 2016 (preliminary) had extremes of abundance in May (low), June (low), and July (high) and an extreme of biomass (April), and extremes in average size in April through June (high), shifting to July (low). Near-average biomass combined with an inverse relationship between abundances and average sizes suggests a dynamic shift in the community composition in 2016, moreso than in other years. The disappearance of large copepods from surface waters (where the CPR operates) in summer is part of the ontogeny of most of the large copepods in the Gulf of Alaska.

b) Coastal - Extrema were numerous off the coast of Oregon in 2015, mostly due to the appearance of numerous taxa of subtropical origin that had not previously been observed in nearly 50 years of sampling. Zooplankton biomass extrema also occurred in 2015 and were stronger off northwest Vancouver Island than southwest Vancouver Is. This pattern suggests a more extreme intrusion of subtropical water than has been observed before.

1.3 Salmon extrema

It was thought desirable to have a standard (comparable) approach to identifying coastwide extrema in salmonid biology. The most common form of salmon data for understanding timing/abundance are the daily counts past observation points. Preferred sites are located before fisheries occur, but these are more rare than sites located after fisheries have occurred. Where fishing is relatively heavy, the resulting observations will no doubt be affected by it. While the tools used to make salmon observations may differ (weirs, test fisheries, sonar), the data generated are suitable for fitting to a common abundance/timing model framework. The migration model developed by Schnute and Sibert (1983) was used because of its flexibility to capture various aspects of a migration. Where complex migrations were clearly evident (e.g. chinook salmon at Bonneville Dam), the data were fit to a complex migration model (McKinnell, unpublished) that allows for mixtures of populations (timing groups) to be identified in a time series. Salmon runs are often a composite of multiple pulses of fish going to one location or multiple populations going to different locations, perhaps each also with multiple pulses of abundance. The parameters estimated for each component include: abundance (A), skewness (S), compression (C), and peak date (P). Abundance is the cumulative total abundance or CPUE (catch-per-unit-effort), skewness measures the degree to which a run deviates from symmetry about an estimate of the peak date, compression measures the fraction of the run passing on the peak date (i.e. related to kurtosis). Peak date is estimated by the model based on the fit of the model to the curve so may differ slightly from the observed peak date. The model was fit to each species in each year to understand the historical interannual variability of each parameter for each run component. The results were placed in rank order to determine if any of the parameters were extrema in 2015 or 2016.

To provide a graphical overview (at the end of Highlights section) of the overall results values of each parameter were classified as high (red) or low (blue) if they were historical extrema in 2015 or 2016. If not, strong anomalies were defined as high (orange) or low (cyan) anomalies if the anomaly exceeded 2 standard deviations from the long-term mean[2], or "normal" within 2 s.d. of the long-term mean. Note that an extremum need not exceed ±2 s.d. Mean size-at-age data, where available, were also ranked to determine if 2015 or 2016 were extrema, strong anomalies or normal using the same criteria. For the most part, environmental extrema are discussed only if they occurred in 2015 or 2016.

1.3.1 Bering Sea

a) Yukon River

- 2015 - highest chinook salmon count at Eagle (near the Alaska – Yukon border).
- 2016 - earliest peak date of chinook salmon and latest peak date of fall chum salmon at Eagle. Latest peak date of pink salmon and least compressed run of summer chum salmon on the Anvik River (tributary 300 mi upstream of estuary)

2 Variable lengths of time series.

b) Bristol Bay

- 2015 - latest migration timing of sockeye salmon return timing ever observed at the Port Moller test fishery.
- 2016 - average weight of sockeye salmon was the smallest observed in 20 years (2.4 kg).

1.3.2 Northern Gulf of Alaska

a) Kodiak

- 2015 - highest count of early-run sockeye salmon and skewed (slow rise to peak) migration of late-run sockeye to Karluk R.
- 2016 - highest count of late-run sockeye salmon and most skewed and compressed returns of pink salmon (early pulse) to the Karluk R.

b) Prince William Sound

- 2015 - Prince William Sound had the largest pink salmon catch on record. Kodiak pink salmon harvest was a strong anomaly (high). There was a strong anomaly (high) in the abundance of early-run Copper River sockeye salmon.
- 2016 - Prince William Sound had the lowest pink salmon catch in 20 years. Russian River - Early-run sockeye salmon was most compressed, and the chinook salmon migration was most skewed and earliest peak date.

1.3.3 Southeast Alaska

- 2015 - There were no harvest abundance extrema in northern or southern SEAK, althought harvest was below average in SSEAK but second highest in the past 20 years in NSEAK (outside), and average in NSEAK (inside). Considering body size, of 10 age/population combinations of sockeye salmon examined, only Chilkoot (age 1.3) had a mean length extremum (small) in 2015. This same population/age-class was also small in 2016.
- 2016 - Pink salmon harvest in NSEAK (inside) was the lowest in the past 20 years, and NSEAK (outside) was the second lowest. SSEAK was below average but not an extreme.
- Coho - No mean size extrema in 2015 nor in 2016 (including data from 2016 troll fishery).
- Chum - 2015 - Chilkat R. only - age 0.3 females were smallest, no extrema for age 0.3 males or age 0.4 males and females.
- Chinook – troll fishery - mean dressed weights in 2015 of age 1.3 and age 0.4 fish were extrema (small) but not for age 0.3 or age 1.4. The dominant feature in these data, across all age-classes, is the declining trend in mean weight over the past 35 years.

1.3.4 British Columbia

The DFO State of the Pacific Ocean report for 2016 (Chandler et al. 2016) provides a good starting point for the present study as it commented on what was known to have occurred in 2015 and what might be expected as a consequence of the environmental conditions that were expected to play out in 2016. Based on what is currently understood about the salmo-environmental linkage, the worst effects of 2015-2016, at least for those in the southern part of the salmosphere, are yet to come.

The 2014-2015 anomalously warm water conditions in the North Pacific Ocean did not induce widespread salmon *recruitment failures in 2015 due to common ocean effects as some feared but, did influence return timing, straying rates and size-at-age traits of many salmon populations originating from eastern Pacific waters from south-central Alaska, through B.C., Washington and Oregon. The impacts of a warmer than average ocean in 2014-2015 followed by the El Niño in spring 2016 suggest survival unfavourable conditions for juvenile salmon making sea entry from the B.C. central to south coast in those years so significant reductions in returns to many populations (Okanagan-Columbia River salmon; Barkley and west coast Vancouver Island salmon) may be expected in 2016-2018.*

a) Nass River (fish wheel)

The data are escapement abundances from 1994. Chinook salmon and sockeye salmon were modelled as having early and late timing components. Coho salmon were modelled as a single pulse as only the first part of the migration is observed before the wheel is shut down for the season.

- 2015 - No timing/abundance extrema in early or late sockeye and chinook salmon, or coho salmon, but the abundances of sockeye and chinook salmon were strong anomalies (low). Sockeye mean size-at-age was an extremum (small) in 2015 in 3 of four age-classes, more extreme for fish that had spent 3 winters at sea.
- 2016 - Early and late-run sockeye salmon and chinook salmon abundances were extrema (high). Early run sockeye and late run chinook had extreme peak dates (late) and for the case of late run chinook salmon, the most compressed run. Coho salmon abundance (till the shutdown) was lowest, most compressed, with the earliest peak date). Mean size-at-age of 4_2 and 5_3 sockeye was small from 2014-2016, but only age 5_3 of the 4 major age-classes had an extremum in 2016.

b) Skeena River (Tyee test fishery)

- 2015 - No timing/abundance extrema occurred in sockeye, coho, pink, and chum salmon and steelhead trout. Chinook salmon had late and compressed timing extrema.
- 2016 - Sockeye salmon migration timing at Tyee was the latest with no other abundance/timing extrema.

c) Docee River (fence count)

- 2015 - no abundance/timing extrema in sockeye salmon.
- 2016 - earliest peak date of migration of sockeye salmon.

d) Fraser River (test fisheries)

The data are pre-fishery abundances (test fisheries) from 2002 to present. Gillnet test fisheries precede seine test fisheries with variable numbers of days of overlap. For simplicity, each time series for each species in each year was modelled as a single pulse of migration. The complexity of decomposing runs of all species, particularly sockeye salmon with different migration timing among cycle years, was beyond the scope of this project.

- 2015 - Of the 60 parameters examined (4 for each time series) in the Johnstone Strait (Round Is. and Blinkhorn) test fisheries, 13 were either extrema or large anomalies. Steelhead trout in the Blinkhorn seine test fishery was the only abundance extremum (high). Pink salmon were early and extremely skewed (sharp drop after an early peak) at Blinkhorn but there were no extrema for pink salmon in the Round Is. gillnet test fishery. Runs of age large sockeye salmon and steelhead trout past Blinkhorn and steelhead trout and coho salmon past Round Is. were the least compressed of all years. Although they were few, timing of age 3_2 sockeye salmon was late at Blinkhorn. Because of their small size, they are rarely caught in gillnet test fisheries. Large chinook salmon were late at

Blinkhorn but not at Round Is. yet both locations had compressed runs.

In the Juan de Fuca test fisheries (gillnet and seine), 16 of 60 parameters examined had extrema or large anomalies. High extrema occurred in the seine fishery (abundances of large and small chinook salmon, and chum salmon) while low extrema occurred in the gillnet fishery (abundances of large sockeye, small and large chinook salmon, and chum salmon). Given that the gillnet fishery starts prior to the seine fishery, this pattern suggests that chinook and chum salmon arrived later than normal, although none were extrema. As in Johnstone St., pink salmon in the gillnet test fisheries at Juan de Fuca did not indicate extrema (except for a skewed migration – slow increase) but the seine fishery did. Pink salmon in the seine test fishery had an early peak and declined more rapidly than in other years. The only other timing extremum was the late peak of coho salmon in the gillnet fishery. The most consistent extrema were found in the compression parameter; most were low values indicating more drawn out migrations. The average weight of Fraser River pink salmon was the smallest ever observed. Total abundance of pink salmon at the Fraser R. was low, much lower than expected, but not an extremum.

- 2016 - The highlight of 2016 was a report by the PSC of the lowest total return of sockeye salmon to the Fraser River since the start of records (late 19th century). Of 52 timing/abundance parameters examined in Johnstone Strait, 14 had extrema or large anomalies. All abundance extrema featured low abundance in seine test fisheries but not gillnet test fisheries (small sockeye, large chinook, and coho salmon at Blinkhorn and large sockeye, small sockeye, large chinook, and steelhead trout in Juan de Fuca). Large sockeye salmon had the earliest peak date in both Juan de Fuca and Blinkhorn test fisheries. At Blinkhorn, the sockeye run was also skewed and compressed (sharp peak). Indeed, all but one (Round Is. chum) of the 13 compression extrema had sharp peaks in 2016. It would be useful to explore the implication for 2017 of low abundances of age 3_2 sockeye salmon in both seine test fisheries in 2016. Extrema in peak dates were few (5) and all but one (steelhead trout at Round Is.) were early.

<u>1.3.6 U.S. Mainland</u>

a) Baker Lake

Data are reconstructed pre-fishery abundances on the Skagit River from 1992.

- 2015 - total returns of sockeye salmon were the highest in the record.
- 2016 – no abundance/timing extrema.

b) Lake Washington (Ballard Locks counts)

The daily sockeye salmon counts at the Ballard Locks were examined.

- 2015 – no abundance/timing extrema
- 2016 – no abundance/timing extrema

c) Columbia River (Bonneville Dam)

Escapement (counts at Bonneville Dam since 1980). Species analyzed included sockeye, large and small chinook, large and small coho, and steelhead trout. Returns of chinook salmon were modelled as 3 pulses, coho salmon as 2 pulses and all other species as single pulses. Data for 2016 included counts to October 21, 2015 except chinook salmon where the counts were re-run later in the season to include data into late November.

- 2015 - The largest total return of large chinook salmon occurred as a result of Summer and Fall Run extrema added to a high abundance of the Spring run. There were no other extrema in this year although sockeye salmon abundance had a strong anomaly (high). Spring and summer small chinook salmon were extremely skewed (peaks in the first part of the run). Small Spring run chinook and large late run coho had compression extrema (low). The only peak date extremum (early) was large early run coho salmon. Although not an extremum of interest to this report, the 2014 ocean entry year produced remarkably few large coho salmon spawners in 2015, considering the sibling relationship that has persisted through the 21st century (see below).

- 2016 - Of 48 parameters examined only 1 was an extremum or strong anomaly and that was the skewed run of steelhead trout (slow rise to a peak).

Body size extrema

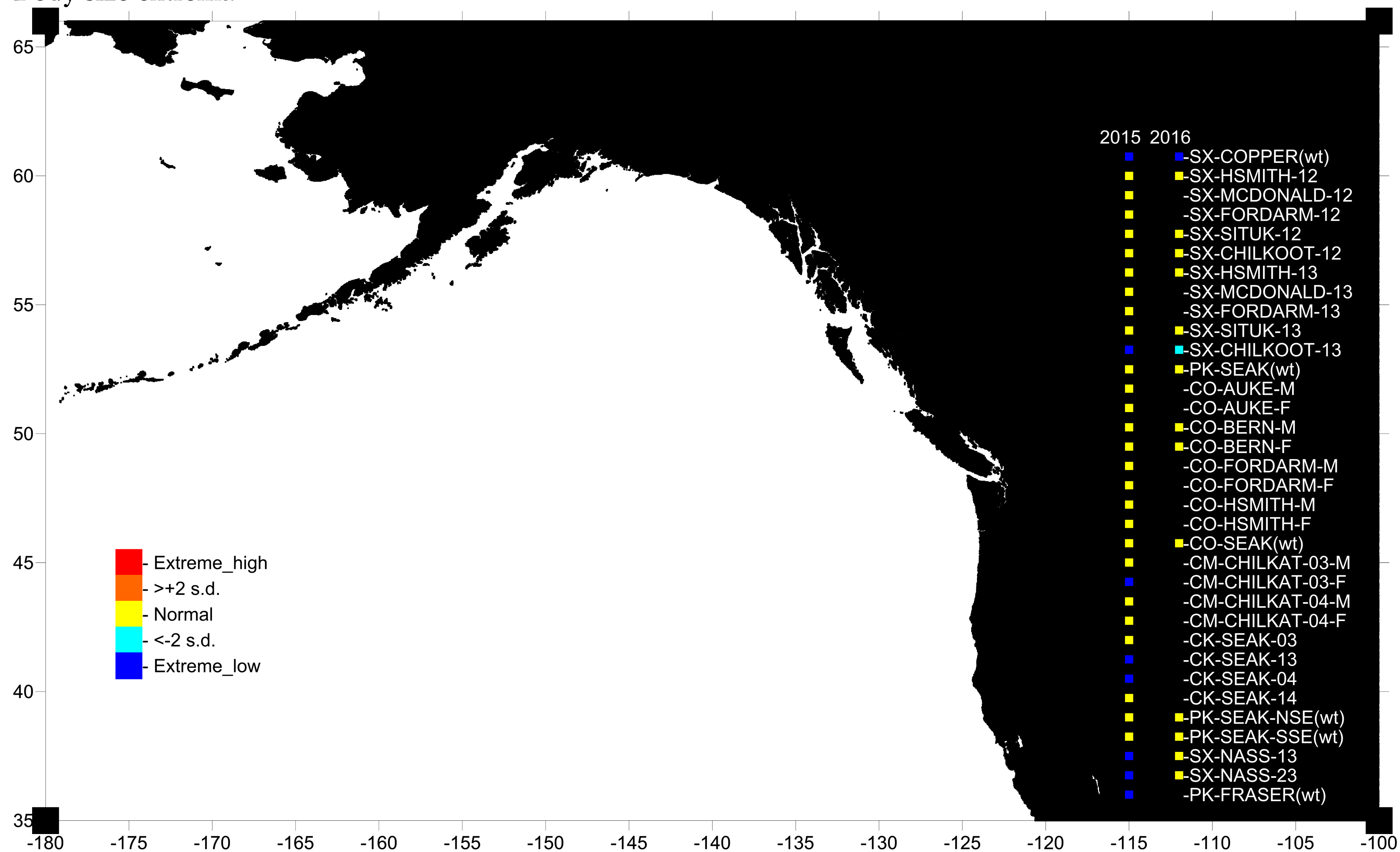

Figure 1: Anomalies and extrema in mean size at age in 2015 and 2016; most are mean length but mean weight is indicated by (wt) in the label. SX-sockeye, PK-pink, CK-chinook, CO-coho, CM-chum, SH-steelhead. Age-at-maturity indicated as two numerals x.y where x-number of freshwater annuli and y-number of ocean annuli. Total age is their sum+1 as there is no annulus formed during the first winter in freshwater (as an egg).

Timing and abundance extrema

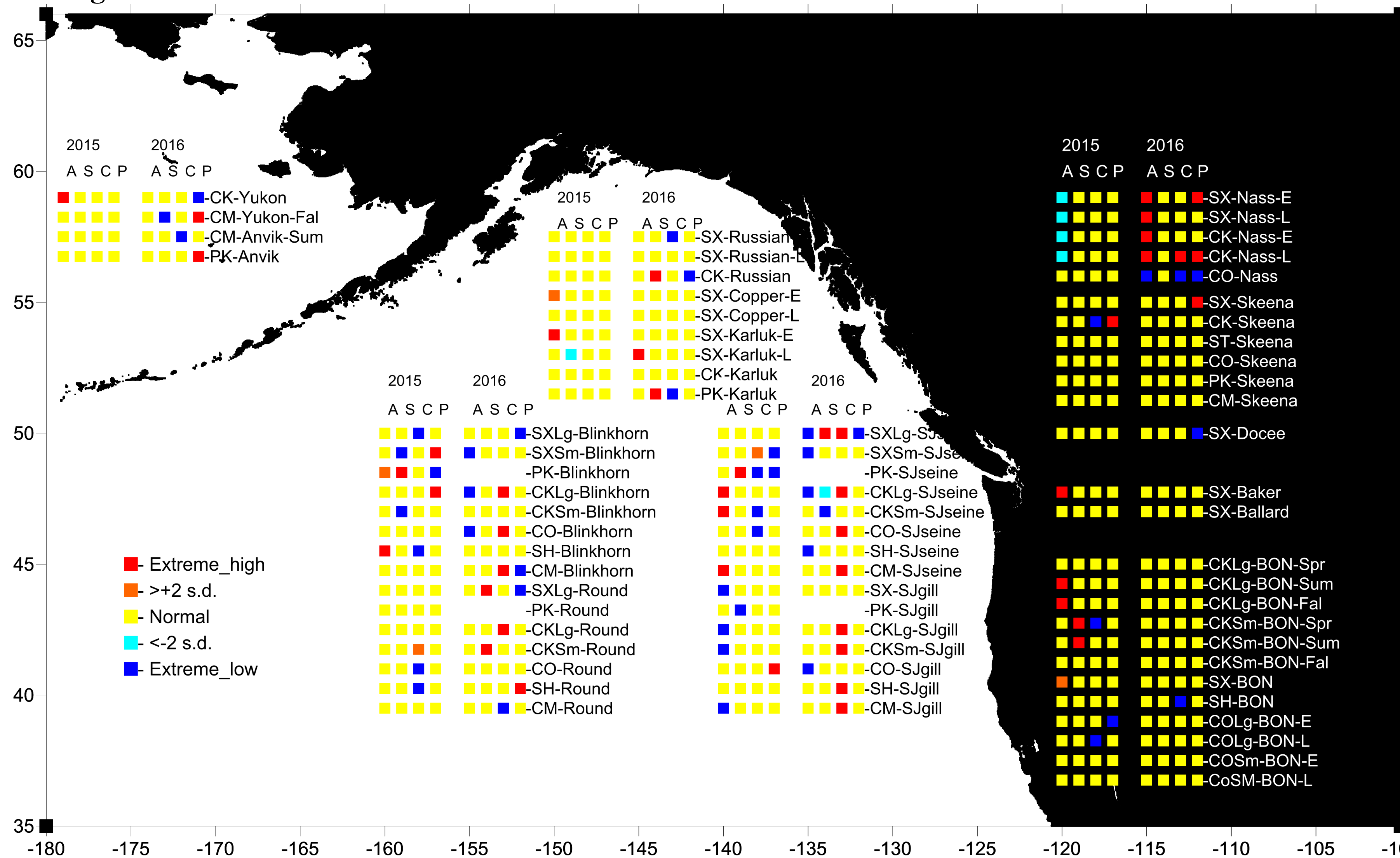

Figure 2: Determination of extrema and strong anomalies in: A= abundance, S= skewness (high [low] values have an abrupt [slow] rise to a peak followed by a long [abrupt] decline), C= compression (high [low] values have a larger percentage of the run passing near the peak date), P= peak date.(high [low] values are late [early]).Lg= large adults, Sm= small adults, E= early run, L= late run, Spr= spring, Sum= summer, Fal= autumn. SX-sockeye, PK-pink, CK-chinook, CO-coho, CM-chum, SH-steelhead. Other location codes are SJ= San Juan, BON=Bonneville Dam.

Introduction

The Northeast Pacific has been experiencing a heat-wave for the last few years (di Lorenzo and Mantua 2016). For marine fish species, the responses to various environmental phenomena, el Niño for example, are often unpredictable (Bailey et al. 1995). Throughout history, outcomes for Pacific salmon arising from an intermittently warmer ocean have varied by species and location. Certainly in the southern extremes of the salmosphere, surface ocean warmth is never considered as a sign of high survival or abundance when juvenile salmon are exposed to it (Mueter et al. 2005). On the other hand, some of the largest adult sockeye salmon returns to the Fraser River have occurred in years when the Gulf of Alaska was much warmer than average, e.g. 1958, 1997 (McKinnell et al. 2012).

At their January 2016 annual meeting, the Pacific Salmon Commission directed the CSC to collaborate with appropriate experts to develop a proposal for annual collation of data on the environment, run size, fish condition, and other metrics that may reveal anomalies in salmon survival. In response, the CSC recommended a two stage approach, the first documenting the 2015 anomalies and the second developing a PSC strategy for ongoing consideration of annual environmental variability and its impact on salmon production and management. The Commissioners directed the CSC to proceed on the first stage of this approach, documenting anomalies in environmental conditions and characteristics of salmon runs in 2015.

A Statement of Work was developed for the author to document 2015 anomalies along with preliminary observations for 2016 where available. The first part was to compile a list of anomalous characteristics of salmon runs in the NE Pacific and potentially linked environmental anomalies in 2015, and similar information for 2016 if available. The CSC will facilitate contacts within State or Federal agencies that can assist with the provision of knowledge and data. The second part, which will form part of the final report, was to conduct a comprehensive evaluation of the identified anomalies which will include:

- Assessment of each anomaly in context of the historical time series, if available.
- Implications of each anomaly to future salmon production, management, forecasting or other Commission interests.
- Recommendations regarding monitoring of each anomaly including consideration of data gaps.

Mapping the salmosphere

In general, existing knowledge of the distribution of salmon in the North Pacific Ocean beyond the continental shelf (excluding the Bering Sea) comes from an intensive period of research that was conducted by Canada, Japan, and the United States during the 1950s and 1960s under the auspices of the International North Pacific Fisheries Commission (INPFC). The Commission was interested in the oceanic distributions of salmon produced by different countries and the extent of their intermingling. Commercial and research catches of salmon on the high seas, primarily using gillnets, provided an understanding of the distributions of each species, whereas floating longline surveys by fisheries research agencies during the 1960s augmented that information with an understanding of the nature of species distributions from different regions. Longline gear was preferred because salmon could be captured alive on the high seas, allowing a tag to be attached to a fish then recovered at some later date by coastal fisheries along the coast during spawning migrations to natal streams. Less often, seine nets were used for the same purpose.

For the present study, the salmosphere in the North Pacific was defined on a 1° grid of latitude/longitude using salmon release locations in the historical high seas tag database (NPAFC 2008), and augmented in the Gulf of Alaska by the locations of longline catches made by Canada from 1961 to 1967, from which many of the tagged salmon were released. A grid point was included in the salmosphere if a salmon of any species had been caught and/or released anywhere within the 1° cell in any year. For the Gulf of Alaska, the merging of longline catches with the historical tag release data created a relatively contiguous region where salmon of any species were caught with few obvious gaps from undersampling (see below). Likewise, grid points in the western North Pacific and parts of the Bering Sea were relatively contiguous, but the central North Pacific had a higher frequency of gaps.

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To fill many of the gaps, a median filter was applied to the data. This filter replaces each grid point by the median value of the surrounding cells. Thereafter, any cell that was obviously missed by the filter was edited manually to create a contiguous domain. Although they form part of the salmosphere, the marginal seas in the northwestern North Pacific were excluded from this analysis. Of course, this approach misses some locations were salmon catches did not occur in these databases which could be improved with additional effort to find them, but for the most part researchers will recognize this domain as that of Pacific salmon. A more rigorous approach would involve defining seasonal salmospheres, perhaps for each species, but that is beyond the scope of the present study. The final grid was used to determine locations where environmental data should be selected to develop salmo-relevant indices of variability.

An Example of the Challenge

The predictability of outcomes for salmon as a consequence of environmental variation in any given year can be relatively poor because mechanistic understanding of cause and effect is not well developed. For example, at the onset of one of the largest el Niños of the 20th century in 1982, a relatively large abundance of age 2_2 coho salmon off the coast of Washington and Oregon that summer was followed one year later by a relatively low abundance (and small mean size) of age 3_2 coho salmon of the same cohort. The dearth of spawners in 1983 was attributed to exceptional mortality at sea during the el Niño (Pearcy et al. 1985). If the el Niño was indeed the cause, one might expect similar kinds of over-winter mortality during other el Niños if the local oceanographic responses to them were similar. The 1997/98 el Niño was a major climatic event (McPhaden 1999) that exhibited most of the classical oceanic and atmospheric responses in the Northeast Pacific. It did not, however, appear to cause unusual over-winter mortality in Washington/Oregon coho salmon when measured as the ratio of the counts of age 3_2 coho at Bonneville in 1998 to age 2_2 counts in 1997. Indeed, the returns of age 3_2 coho salmon to Bonneville Dam in both 1983 and 1998 were about what would have been expected from the sibling relationship of that era (but not of the recent era)(Figure 3). If there had been anomalously atypical over-winter mortality in 1983, a strong outlier might have been expected in 1998, but it did not occur. So it seems rather difficult to reach

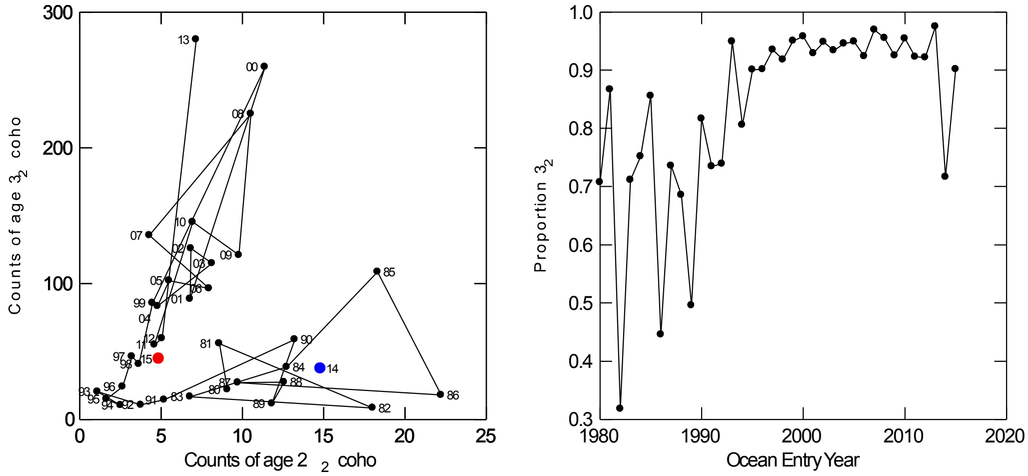


Figure 3: [left] Counts of age 3_2 coho salmon (ordinate) versus counts of age 2_2 coho salmon of the same cohort (abscissa). Plot point labels indicate ocean entry year of the cohort. Years are linked in sequence by black lines.[right] Data from the panel on the left expressed as proportion of age 32 spawners in each cohort. The 2013 ocean entry year produced the greatest number of total coho salmon spawners in the record. The 2014 ocean entry year (blue dot), while having relatively large numbers of age 2_2 spawners saw remarkably few age 3_2 spawners of the same cohort the following year; a ratio that had not seen since the 1980s. Despite some of the highest juvenile growth rates ever observed, the 2015 ocean entry year (red dot) produced few spawners.

the general conclusion that el Niños kill coho salmon. What is more apparent is the division of the time series into two stanzas around the mid-1990s.

Two possible causes for a fundamental change come to mind. The first is that since the late 1990s, a greater proportion of a cohort of coho salmon (those ascending above Bonneville Dam) have delayed maturity until after one full year at sea (Figure 3, right) rather than ascending the river to spawn after one summer at sea. Likewise, the apparent change in maturity schedule could arise if late-stage mortality was more prevalent prior to the late 1990s. Generally, however, smolt to adult survival of coho salmon was greater before the 1990s than after, which tends to support the idea of a fundamental shift in the maturity schedule of these fish. Delaying maturity is one of the responses by salmon to reduced growth. On average, older maturing salmon tend to exhibit slower growth throughout their lives (Bilton 1971, McKinnell 1995). As age-at-maturity in coho salmon may be determined in freshwater prior to seaward migration, the maturity schedule is not likely determined solely in the ocean. As most coho salmon above Bonneville Dam are from hatcheries, perhaps there was a change in some aspect of feeding that led to the change in maturity schedule.

The return of age 3_2 coho salmon to Bonneville Dam in 2014 was a recent extremum (high). Likewise, the return of age 2_2 was the 4^{th} largest since the 1980s (Figure 3). The 2015 return year (2014 OEY) of age 3_2 coho salmon failed to match the abundance of that cohort seen the previous year. Indeed, that return in 2015 was what might have been expected under the sibling relationship that existed during the 20^{th} century when high age 2_2 abundances were associated with much lower returns of siblings the following year. Juvenile coho salmon growth off Washington and Oregon was high in 2014 (B. Beckman, NOAA/Seattle, pers. comm.) and highest in a 20 year record off the West coast of Vancouver Island (Chandler et al. 2016). Therefore, the low abundances of age 3_2 coho salmon at Bonneville in 2015 are more likely due to late-stage mortality, than a change in the maturity schedule, all else held constant.

Environmental extrema

The primary focus of this study is extrema that occurred in 2015 and 2016, yet the dominant cause of environmental variation in the salmosphere is the seasonal (annual) cycle of warming and cooling associated with the Earth's orbit around the sun. The general practice for studying unusual events is to begin by removing the effect of the seasonal cycle from the data by subtracting off seasonal average values. For example, the monthly average temperature in June 1977 at some location is transformed into a temperature "anomaly" at that location by subtracting the long-term average for the month of June from the June 1977 value. With daily data, the long-term daily average would be removed. Anomalies can be either positive or negative and the larger they are, the more extreme is the non-seasonal anomaly. The largest of these, of either sign, is what is sought in this study.

1. Surface air temperature (SAT)

Di Lorenzo and Mantua (2016) describe a marine heatwave in the Gulf of Alaska in 2014-2015 but it seems that there is evidence in the atmosphere for it starting in June of 2013, and that it continued well into 2016. Using the U.S. NCEP/NCAR Re-analysis 1 data (Kalnay et al. 1996), restricted to the Pacific salmosphere, SAT extrema (maxima) at individual grid points (2.5º x 2.5º latitude/longitude) are far more numerous from 2014 to 2016 than in other years (Figure 7). The greatest number of SAT extrema (maxima) observed in any one month since 1948 in the salmosphere occurred in August 2016 (31% of the entire Pacific salmosphere). The greatest number of extrema (maxima) observed in any month in 2015 was of similar geographic scale, but they occurred in the month of February. The range of latitudes of SAT maxima was more widespread in February 2015 than in August 2016 (Figure 5).

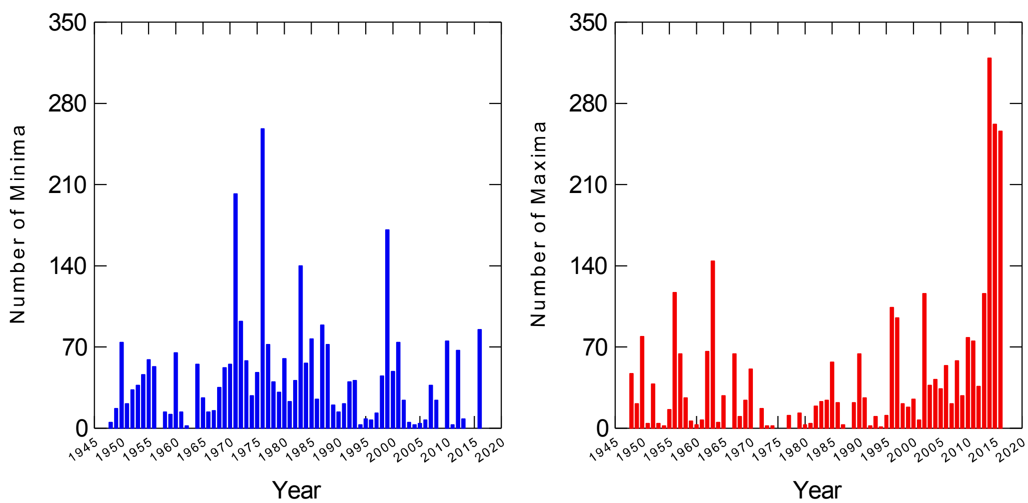


Figure 4: Number of surface air temperature minima (left) and maxima (right) by year in the salmosphere since 1948 to 2016 (September). Data source: NOAA/NCAR Re-analysis.

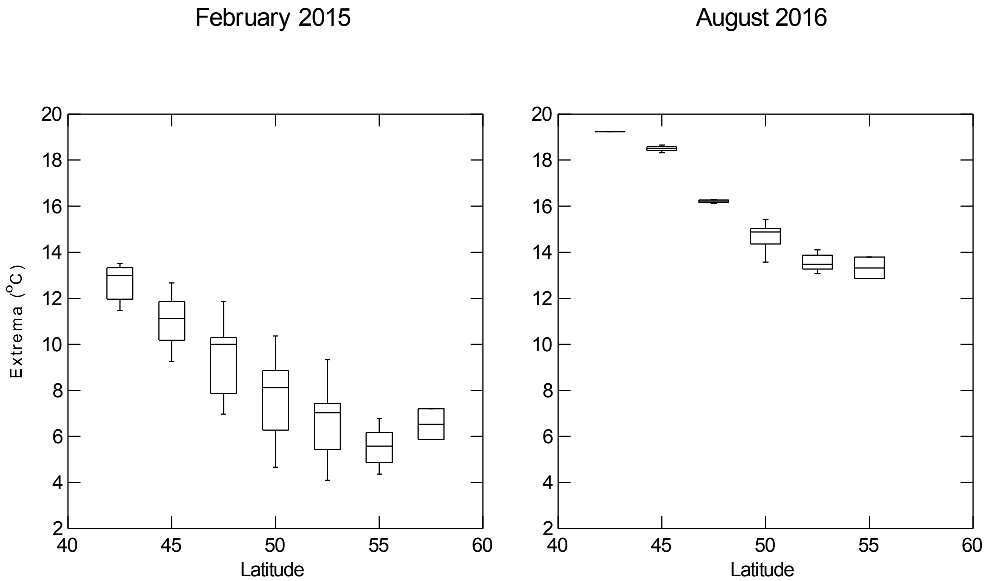


Figure 5: Surface air temperature (SAT) extrema by latitude (across longitudes) in the Gulf of Alaska (east of 165°W) in months when extrema were most frequent. The single horizontal bar at 42.5°N indicates that only one longitude at that latitude had an extreme SAT.

Principal Component (PC) analysis of monthly SAT anomalies (SATa) in the North Pacific salmosphere since 1948 suggests that SATa variation is associated with two independent forces of nearly equal weight (27.6% for PC1 and 23.5% for PC2). The spatial pattern of PC1 (Figure 4) is an east-west dipole (seesaw) with an alternation between warm in the West and cool in the East and *vice versa*, i.e. like the subarctic portion of the Pacific Decadal Oscillation of SSTa (hereafter the SalmoDO, see Figure 16 below) but in the atmosphere. The correlation between SATa-PC1 and the SalmoDO was maximum (0.77) in May. PC2, on the other hand, is a salmosphere-wide phenomenon that is associated with the Victoria Pattern of SSTa variation (also related to the NPGO-North Pacific Gyre Oscillation). It was the Victoria Pattern that shifted abruptly to positive between May and June of 2013 and the change has persisted to at least October 2016 (Figure 6). The average increase in PC2 after June 2013 was +1.9 s.d. higher than the average of the 65 year period that preceded it. This analysis found that only April 2016 was an extremum of PC1 in any month. In the months of January and February, only 1977 exceeded 2016 in magnitude of PC1 scores. There were no extrema of PC1 in 2015. PC2, on the other hand, had extrema in February and October of 2015 and July and August of 2016.

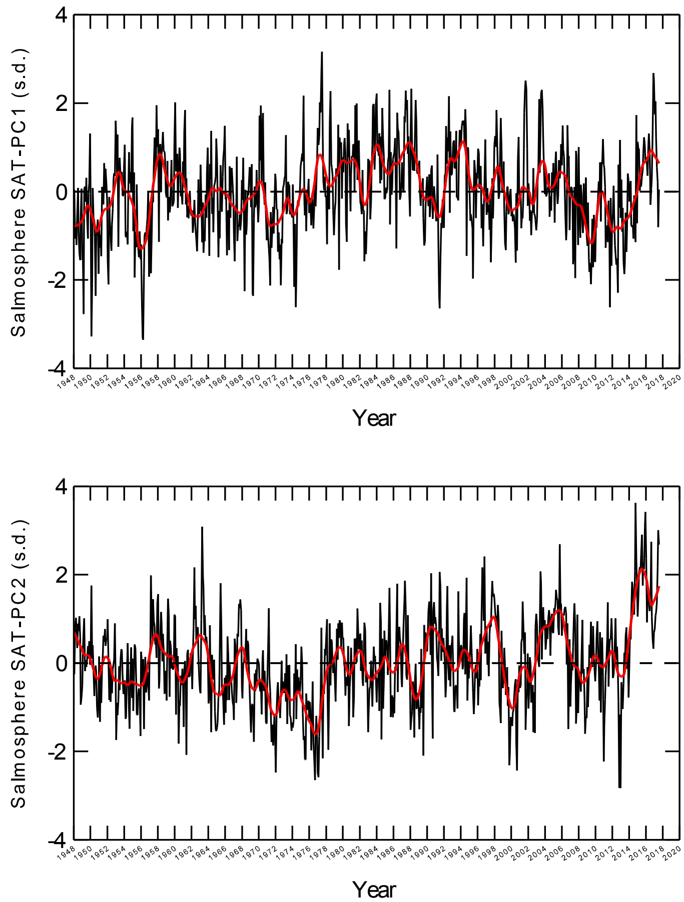


Figure 6: Principal components 1 (above) and 2 (below) of SAT anomalies in the salmosphere from 1948 to September 2016.

2. Sea level pressure (SLP)

Storms in the salmosphere and elsewhere are recognized as depressions in the sea level pressure field. Strong storms are associated with stronger, larger depressions. Integrating the pressures within these depressions over some sensible period of time generates an index of storminess during that period. Although various indices of winter storm intensity exist (North Pacific Index – Trenberth and Hurrell 1995), Aleutian Low Pressure Index (McFarlane and Beamish 1992), they have spatial domains that extend well into the subtropics. The Aleutian Low Integral Index (ALII – McKinnell 2016) was modified to compute an index of average winter (DJF) storminess in the salmosphere alone. The result was an index with high interannual variability and no trend after the 1976/77 climate regime shift. Neither the winters of 2015 nor 2016 were remarkable across the entire domain (Figure 8), but if the spatial domain is restricted to the eastern portion of the Pacific salmosphere (east of 180 º longitude), the winter of 2016 was the 3rd highest in the time series, lagging only the 1983 and 1998 el Niños. The "knock-on" effects of a stormy winter are discussed in the section on mixed layer depth.

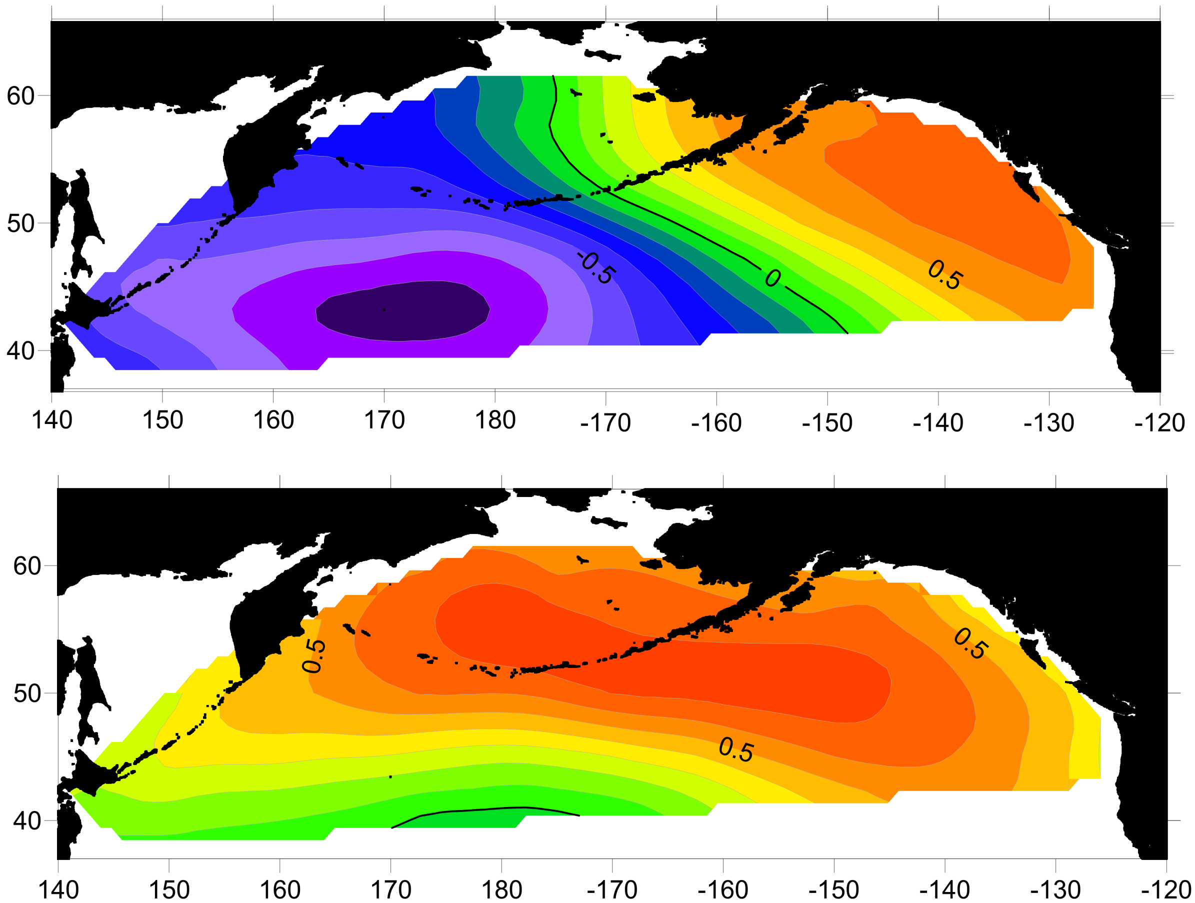


Figure 7: Spatial patterns of PC1 (above) and PC2(below) of monthly surface air temperature anomalies in the salmosphere from 1948 to 2016.

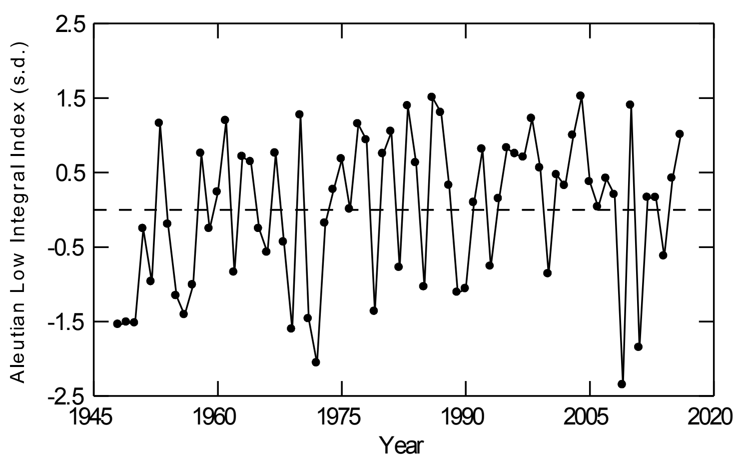


Figure 8: Aleutian Low Integral Index (ALII) is the integral of monthly sea level pressures < 1008.5 hPa, in this case restricted to locations lying within the Pacific salmosphere. This figure indicates the winter (DJF) average values to 2016.

3. Sea surface temperature (SST)
   Separate analyses were conducted to examine the two dominant phases of the oceanic life of salmon. Juveniles are generally restricted to the continental shelf during their early life history (Hartt and Dell, 1986; Grimes et al. 2007), whereas older immature salmon and maturing salmon, particularly the planktivores, occupy the deeper waters. Perhaps a more appropriate approach would be to further subdivide the salmosphere into a cohosphere, etc. as oceanic distributions vary by species, however, that level of detail was beyond the scope of this project. To capture finer scale variability on the narrow continental shelf, defined as depths <1500 m, daily SST data on a ¼° grid were used rather than monthly average 1° grid used for the oceanic region.

3.1. Continental shelf

SST measured daily at one lighthouse on Kains Island (Northwest Vancouver Island) reflects the SST variation that is occurring across a broad range of latitudes along the coast and even into the Gulf of Alaska (McKinnell et al. 1999). The nature of this coastwide (defined here as depths <1500 m) covariation was studied using principal components analysis by computing daily SSTa measured by satellite on a spatial grid from California to Alaska. The dominant component of non-seasonal SST variability (PC1) had loadings of the same sign extending from Cape Mendocino, CA to Prince William Sound, AK with the maximum located in central Queen Charlotte Sound, BC (Figure 6). PC1 accounted for 55% of SSTa covariation and its loadings tended to increase away from land, likely because of local SST variability added by buoyancy-driven coastal currents (e.g. Alaska Coastal Current versus the large-scale circulation of the Alaska Current) and coastal upwelling, primarily along the U.S. West coast. The lowest correlation of SSTa with PC1 at any location on the shelf was r = +0.4 indicating that the entire coast is correlated with this pattern suggesting that non-seasonal SSTa variation on the continental shelf is due to large-scale environmental forcing.

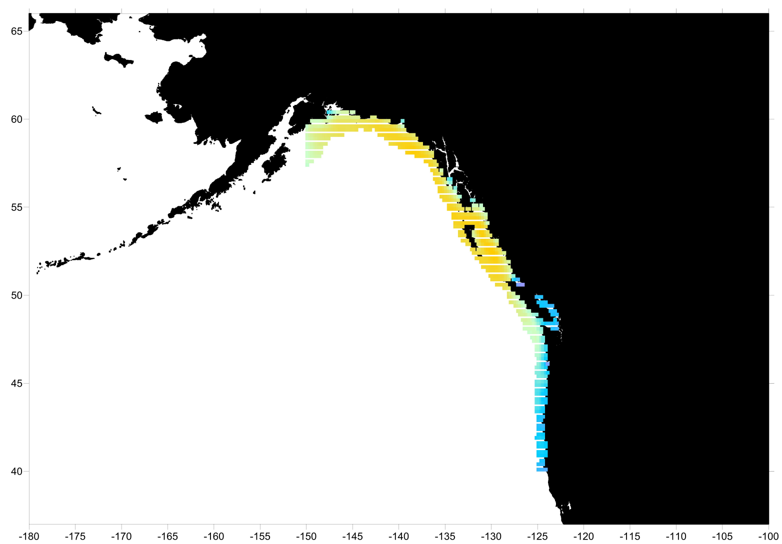


Figure 9: Correlations (loadings) between daily sea surface temperature anomaly variation (0.25° spatial grid) and SST-PC1 are shaded in

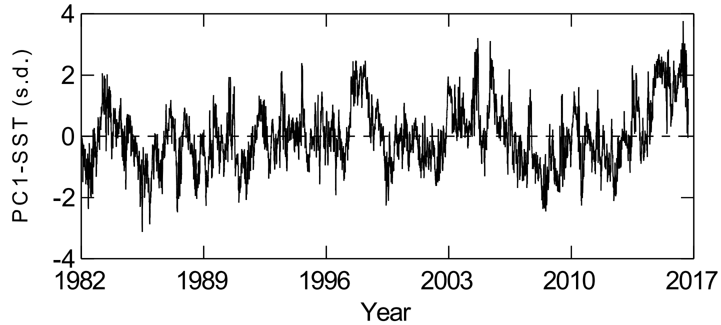


Figure 10: Daily temporal variation of SSTa-PC1 on the continental shelf to the end of October, 2016.

Considering temporal variation in coastal SSTs, a number of interesting features are evident. PC1 scores were generally negative (cool) for an extended period from 2006 to mid-June of 2013 when there was an abrupt warming that abated briefly in August 2013 before returning to strongly positive (warm) scores in September that persisted through the fall of 2013 before returning to negative (Figure 9). Thereafter, PC1 scores continued at relatively neutral values until the beginning of May 2014 when they became strongly positive for a few weeks. This warm spell abated briefly in mid-June then shifted to positive scores for the longest uninterrupted period since 1982. Apart from two days (August 22 and 23, 2016), PC1 has been continuously positive since June 27, 2014 (to Dec. 29, 2016), a period of 956 days. The previous record of continuously positive PC1 values was 428 days during the last major el Niño in 1997/98. Of note, the latter featured values of PC1 that were comparable with those observed since 2014 (Figure 10). Periods of unusually high surface temperatures along the North American coast occur with some regularity at bidecadal intervals and this event was not unexpected (McKinnell and Crawford 2007).

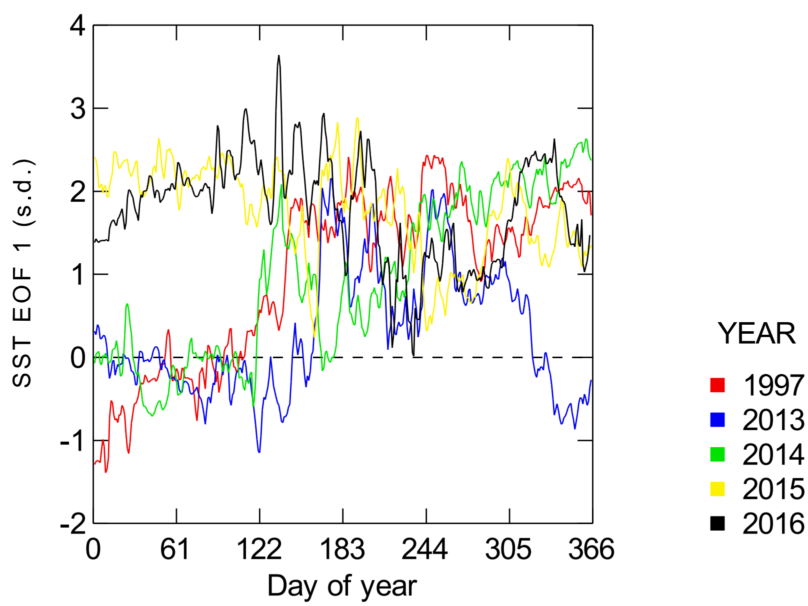


Figure 11: Continental shelf variation in PC1 of SSTa covariation from California to Alaska; only years 2013-2016 are shown, along with 1997 when the last blob hit the BC coast.

The three highest positive PC1 scores (>3.6 s.d.) occurred over a 3-day period, May 14-16, 2016 (Figure 10). The next 6 highest scores occurred in 2004 and in 2005. In 2015, the rank of the strongest positive score that year occurred on July 12th and it was 19th highest in the entire record, from 1981. The strongest positive score in 2014 (50th highest) occurred on December 27. There is little evidence of an overall linear trend in this PC1 time series. If the recent stanza of strong PC1 scores from 2014 is excluded, there is no statistically significant linear trend in PC1 from 1982 to 2013.

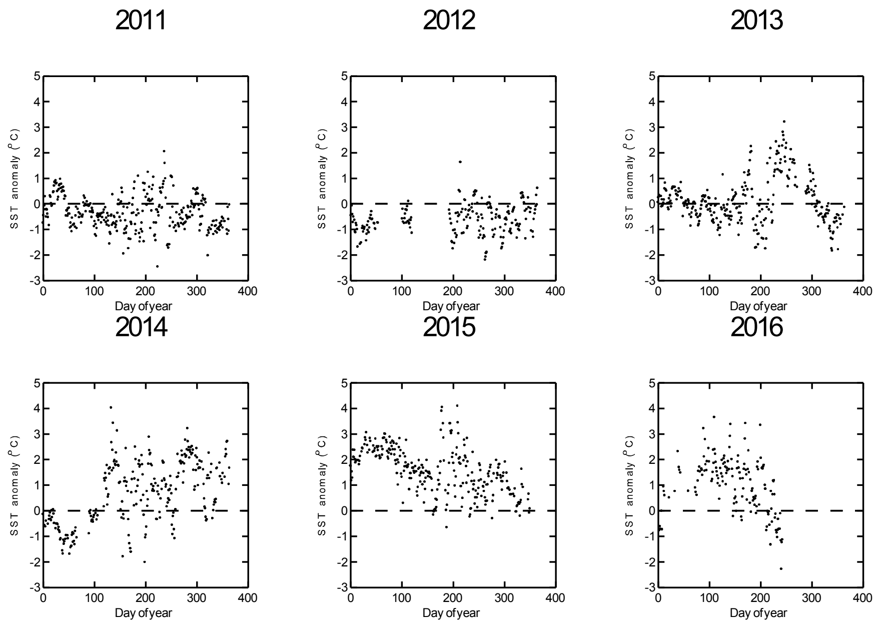


Figure 12: SST anomalies at Kains Island (NW Vancouver Island) by year from 2011.

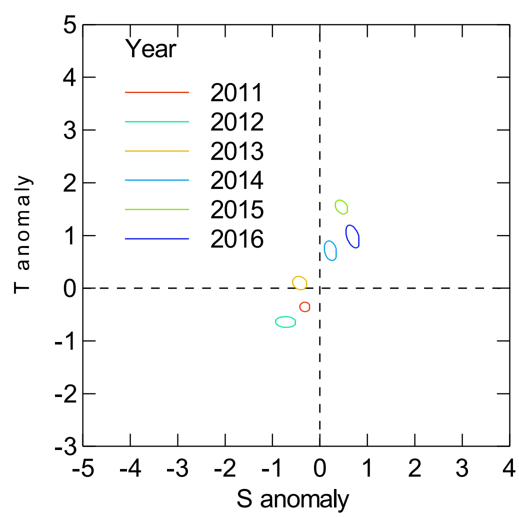


Figure 13: Bivariate ellipses indicate the location of the annual bivariate average of temperature and salinity anomalies at Kains Island. 2014-2016 are in the top right quadrant with 2015 the most extreme in the 82 year history.

Returning to Kains Island to gauge the local effect, SST and SSS have been recorded daily almost continuously since 1934. The coastwide pattern of high values of SST-PC1 that occurred throughout 2014 did not begin at Kains Island until the beginning of May of that year (Figure 11). These strong positive anomalies were also accompanied by positive salinity anomalies rather than the normal negative anomalies (Thomson and Hourston 2010). By 2015, the combination of high SST and high SSS, sometimes called s*picy* water, was the highest observed bivariate annual average and it has persisted at least to August 2016 (Figure 12). As the salinity gradient away from Kains Island is increasing seaward, the appearance of spicy water suggests and offshore and perhaps southerly origin.

a) Chilko L. sockeye marine survival and coastal SST

There is a single timeseries of annual postsmolt survivals for Chilko Lake sockeye salmon that dates to the 1950s. If annual survival is compared with values of PC1 during ocean entry, from 1982 to 2014, the result confirms traditional scientific knowledge that warmer coastal SSTs are never good for survival of Fraser River sockeye salmon. Negative correlations between survival and PC1 scores were largest during a period between the summer solstice and the fall equinox (Figure 13).

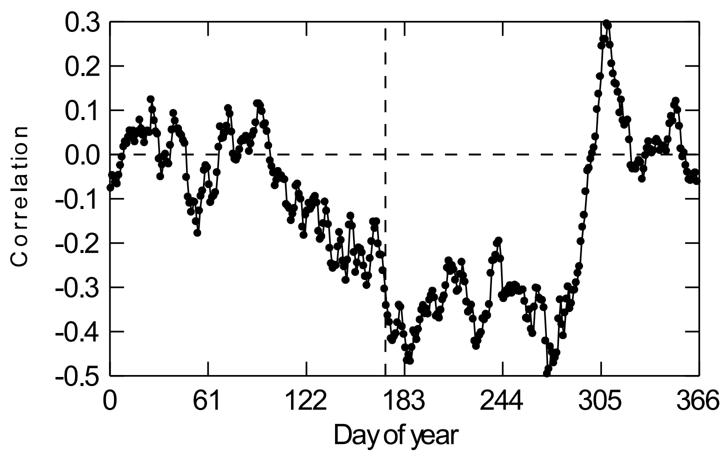


Figure 14 Correlations, calculated daily, between PC1 scores and annual postsmolt survival for Chilko Lake sockeye salmon. The vertical dashed line indicates the date of the summer solstice (June 21). At best, PC1 accounts for about 25% of annual variation in survival during the period from the summer solstice to the autumnal equinox, a period when the salmon are assumed to be on the continental shelf.

So the coastal environment is generally uncorrelated with Chilko Lake sockeye salmon postsmolt survival during winter when the fish are still in the lake. Through the spring the negative correlations gradually strengthen until an abrupt decrease occurs near the solstice, the time when these postsmolts are leaving inside waters. By November and December the correlation returns toward zero. This pattern suggests that there is no reason to expect that average to good survival will arise from the 2014-2016 ocean entry years, adult returns largely in 2016-2018.

3.2. Offshore SST

Monthly SSTa variability in the salmosphere offshore is dominated by an east-west dipole (seesaw) with centres of action in the Gulf of Alaska to the east and a widespread region associated with the Kuroshio-Oyashio mixing region in the western North Pacific (Figure 16). This pattern (SalmoDO – Salmosphere Decadal Oscillation) accounts for 34% of the covariance of SSTa in the Pacific salmosphere. As might be expected, the SalmoDO is correlated with PC1 of SATa (r = 0.5) but it is slightly more correlated with PC2 of SATa. The central North Pacific, southr of the Aleutian archipelago varies from weakly correlated to uncorrelated with the SalmoDO pattern as its location lies between the two extremes of the dipole. The most extreme positive value of PC1 occurred in September 2014 (Figure 14) and 17 of the top 25 extreme values of the SalmoDO occurred from January 2014-August, 2016. Only 1997 (July to September) had more than one extremum in the top 25. Some may recall that the summer of 1997 was the year of the widespread straying sockeye salmon phenomenon that affected, primarily, Fraser R. populations (McKinnell 2000). Many sockeye salmon abandoned their migration to spawn in rivers along the migration route because they had begun to develop secondary sexual characteristics maturing while still at sea. The 4th highest value in the PC1 time series occurred in November 1986 but it did not appear to lead to noteworthy biological phenomena. Apart from a one month excursion into the negative in October 2013, the SalmoDO has had strong positive values since July 2013. Comparing the SalmoDO with the PDO finds that only half of the variation in the SalmoDO is associated with the PDO. The correlation between the SalmoDO and the PDO is strongest (r > 0.8) from November to April and weakest in summer (August r = 0.5). PC2, the subdominant pattern (24% of covariation), primarily captures SSTa variations in the western North Pacific so it will not be discussed further. It is highly correlated with PC2 of SATa, but only in the summer months.

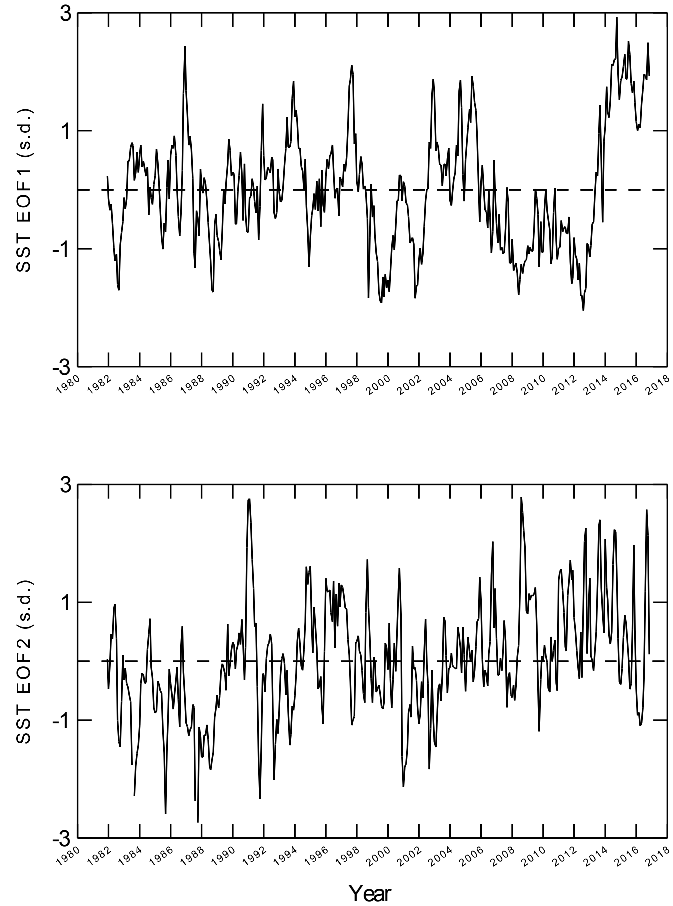


Figure 15: Temporal variation in PC1 (above) and PC2 (below) of monthly sea surface temperature anomalies in the salmosphere from November 1981 to October 2016.

3.3. Offshore (Project Argo)

The advantage of using satellites to measure SST is broad spatial coverage, but these measurements will tend to over-estimate the temperatures experienced by salmon because oceanic habitat lies beneath the surface where temperatures are generally cooler during the warm season . Project Argo (http://www-argo.ucsd.edu/) has populated the World Ocean beyond continental shelves with >3000

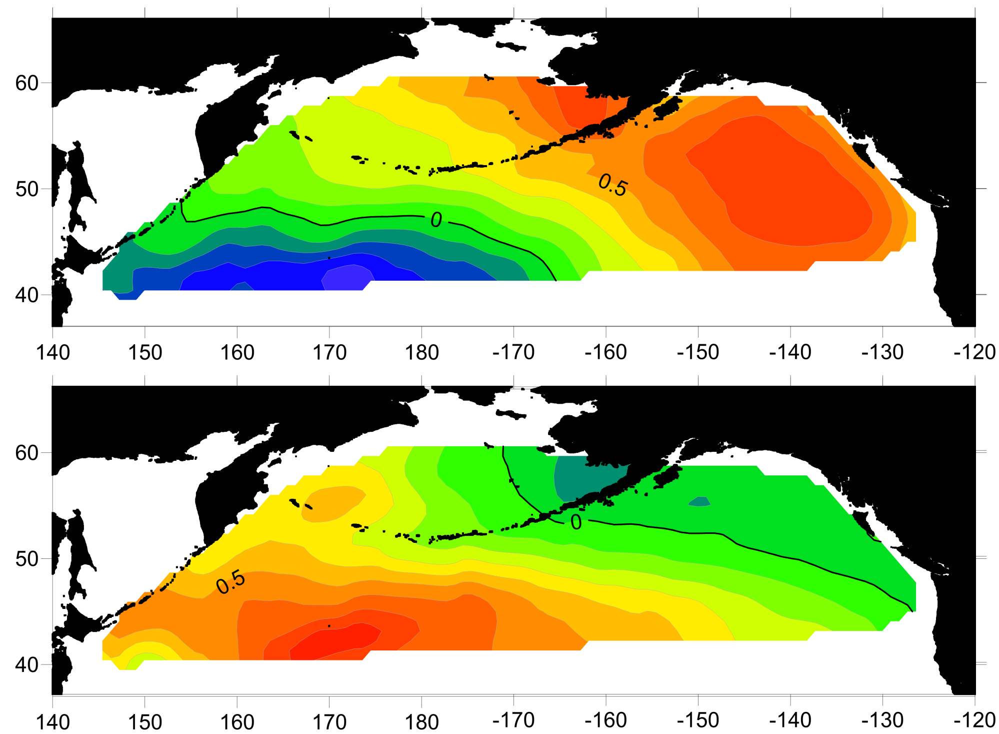


Figure 16: Spatial distribution of PC1 (above) and PC2 (below) of monthly sea surface temperature anomalies in the salmosphere, 1981 to present. The spacing between contours, indicated by difference colours, is 0.1.

profiling floats that measure temperature and salinity at depth and transmit the results via satellite to centres that distribute the data globally without charge. The Argo data allow water properties to be examined to a depth of 2000 m. For the present study, temperatures at 5 m depth were examined initially and compared with satellite based SST at or near (within) the float location to determine whether the temperature extrema in the Northeast Pacific were simply a very near surface effect, and if not, to determine the extent of the extrema with depth.

3.4. Temperature at 5 m depth

As the uppermost depths of the measurements made by the profiling floats are commonly near 5 m, all temperature and salinity readings found in the range 4 – 5.5 m in the salmosphere were selected for further analysis. See Appendix 1 for discussion of computing anomalies. A box and whisker plot (Figure 14) of all anomalies shows the range of variation found each year. Outliers in the range of ±3°C are common in the eastern salmosphere but most of the anomalies every year, as indicated by the box are < ±1°C. There are clearly more extrema in 2016 than in any other year, although the median anomaly in 2015 was slightly higher than all other years. The highest positive anomalies occurred between 48° - 50°N

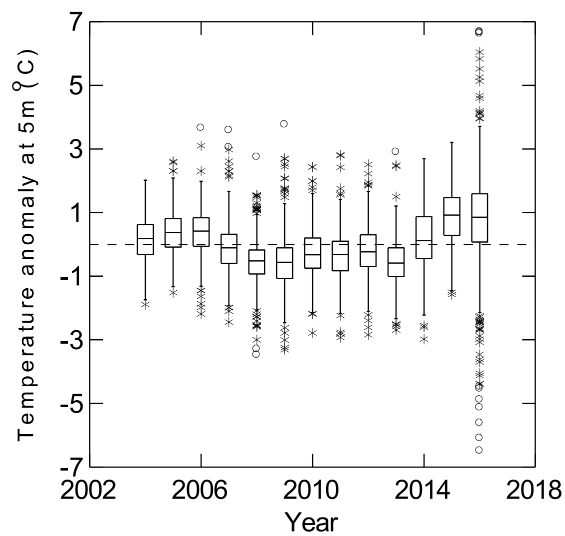


Figure 17: Box and whisker plots of monthly average temperature anomalies at 5 m depth in 2x5 latitude/longitude blocks in the salmosphere (east of 180 longitude).

(south of the Aleutian archipelago) while the most negative anomalies at about the same longitudes, were in the south 40°-42°N (Figure 15). The strongest anomalies in 2016 occurred between 180° and 170°W which is beyond the historical range of migration of many salmon populations in the eastern Gulf of Alaska.

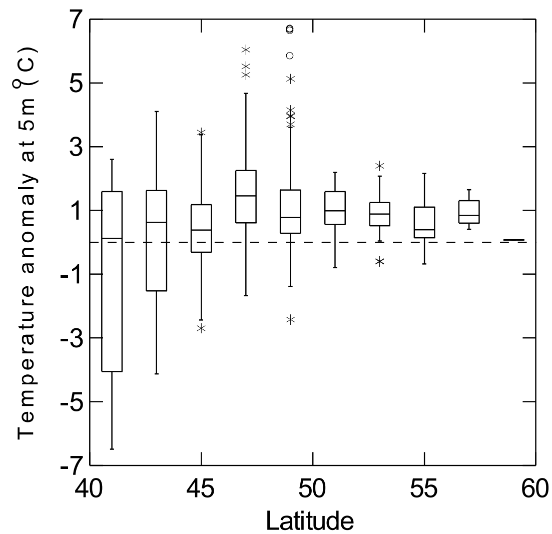


Figure 18: Temperature anomalies by latitude in the salmosphere in 2016.

3.5. Salinity at 5 m depth

In broad terms, salinity anomalies in the eastern salmosphere corresponded with, and likely contributed to the temperature anomalies. While the temperature anomalies were generally warm from 2003-2005, there was a sustained cool period thereafter that lasted until 2013. The salinity anomalies were generally fresh then salty, then fresh again during the heat-wave (Figure 20). Like the temperature anomalies, the largest salinity anomalies occurred in 2016 and were located near the international date line, although there were one or two strong anomalies adjacent to the North American coast. The inverse relationship between SST and SSS anomalies was described by Thomson & Hourston (2010).

3.6. Salmon and the Blob

Although the Blob covered much of the surface of the northeastern North Pacific, its centre of mass at least in its earliest stages was not in the subarctic (Figure 19) and coastal SSTs during to the end of April 2014 at Kains Is. were normal (Figure 11). Based on weekly SST data on a since 1981 there have been 11,244 weekly anomalies somewhere in the North Pacific (north of 20° N) that have exceeded +3 s.d. above the long-term mean for any particular time and location. From 2014 to 2016, the total number of these strong SST anomalies exceeded all other years. Most of these extremes occurred beyond the salmosphere, but that maybe simply from greater opportunity to exhibit a strong anomaly; there are many more grid points in the subtropics because the continents diverge with decreasing latitude.

Most of the large positive SST anomalies in 2014 occurred in January and February between 40°N to 50°N, 160°W to 140°W in the central Gulf of Alaska (Figure 17). That location places the strongest influence of this winter blob on the southern fringe of the salmosphere, although lesser positive anomalies certainly extended northward. While the range of salmons extend south of 50°N, they are not very abundant at these latitudes except in the western Pacific.

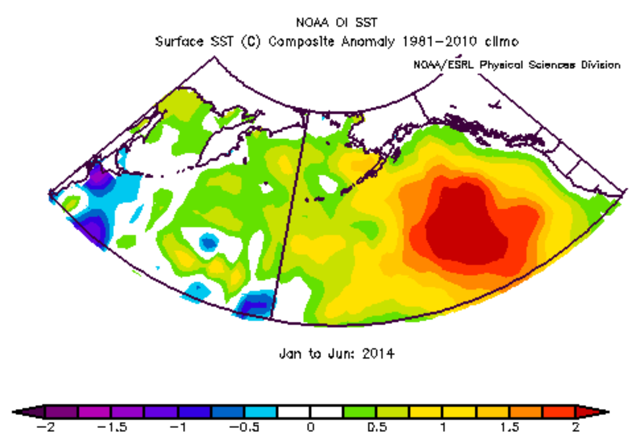


Figure 19: The Blob - an SST anomaly pattern in the Northeast Pacific (January - June 2014 average shown here).

By examining all Argo profiles within the "blob domain" of early 2014, it is clear that it penetrated to about 90 m depth which is approximately the depth of the mixed layer in winter. The maximum depth of the 2014 anomaly was determined by taking slices of 10 m from the surface to depth and computing the average of all observations in each layer. Since 2002, the year 2014 had the highest average temperature in all layers down to 90 m, according to an ANCOVA (to control for the effect of latitude). At greater depths, 2015 had the highest average temperatures in all 10 m layers down to 150 m. In 2015, most of the strong positive SST anomalies occurred off Canada and the U.S. West coast in a zone that essentially highlighted the California Current region from its source near Queen Charlotte Sound to its recirculation into the subtropical North Pacific. This eastern blob in 2015 had a similar temperature vs. depth structure to the one found further offshore in 2014. Average temperature by 10 m layer in the eastern blob was highest in 2015 for all layers down to 100 m, and thereafter 2016 temperatures became higher than 2015. Although most of the discussion is about the magnitude of anomalies, it is perhaps more important to consider the absolute values of the SSTs at locations where there were strong departures from average as the SSTs may or may not be physiologically stressful.

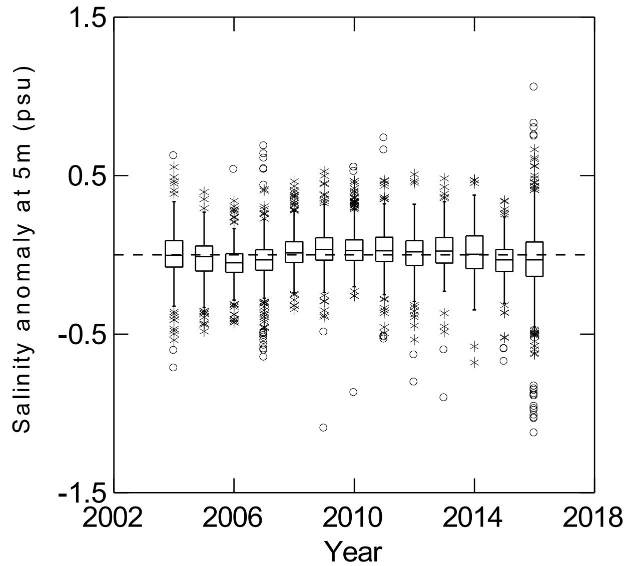


Figure 20: Box and whisker plot of salinity anomalies at 5 m depth in the eastern salmosphere.

4. Mixed Layer Depth (MLD)

The salmosphere has a strong vertical density gradient with lighter water sitting on top of heavier water, primarily caused by a vertical salinity gradient (fresh water floats on salty water) (Favorite et al. 1976). This gradient is enhanced seasonally during summer because the sea surface is warmed by solar radiation which increases the gradient, as does melting sea ice where it exists. The combination of a stronger gradient and lighter winds in summer limits the depth of vertical ocean mixing in summer approximately to the upper 25 m. Nutrients beneath the depth of the mixed layer are not available to support phytoplankton growth. Energy, primarily from stronger winds, is needed to break down the gradient in the fall and recycle nutrients back into the surface layer. In the Gulf of Alaska the mixed layer depth (MLD) is of the order of 80-125 m in winter. The exact depths depend to a certain degree on how the depth of the layer is calculated and in this report, MLD was calculated as the depth of a surface layer of uniform density. Despite a relatively stormy winter of 2014/2015, the January-April MLD anomalies of 2015 were the most extreme (shallow) anomaly in the record. This suggests that the vertical stability that had built up during the heat wave of 2014 was not destabilized by the stronger than average winds that occurred in the winter of 2014/2015. One expected result of a shallow winter MLD is low nutrient concentrations in the surface layer and this is exactly what was found on DFO's Line-P cruises in 2015 (Figure 21) where the winter nutrient (nitrate) supply in the winter of 2015 (Figure 21, top right) was the lowest observed on Line-P in the past seven years.

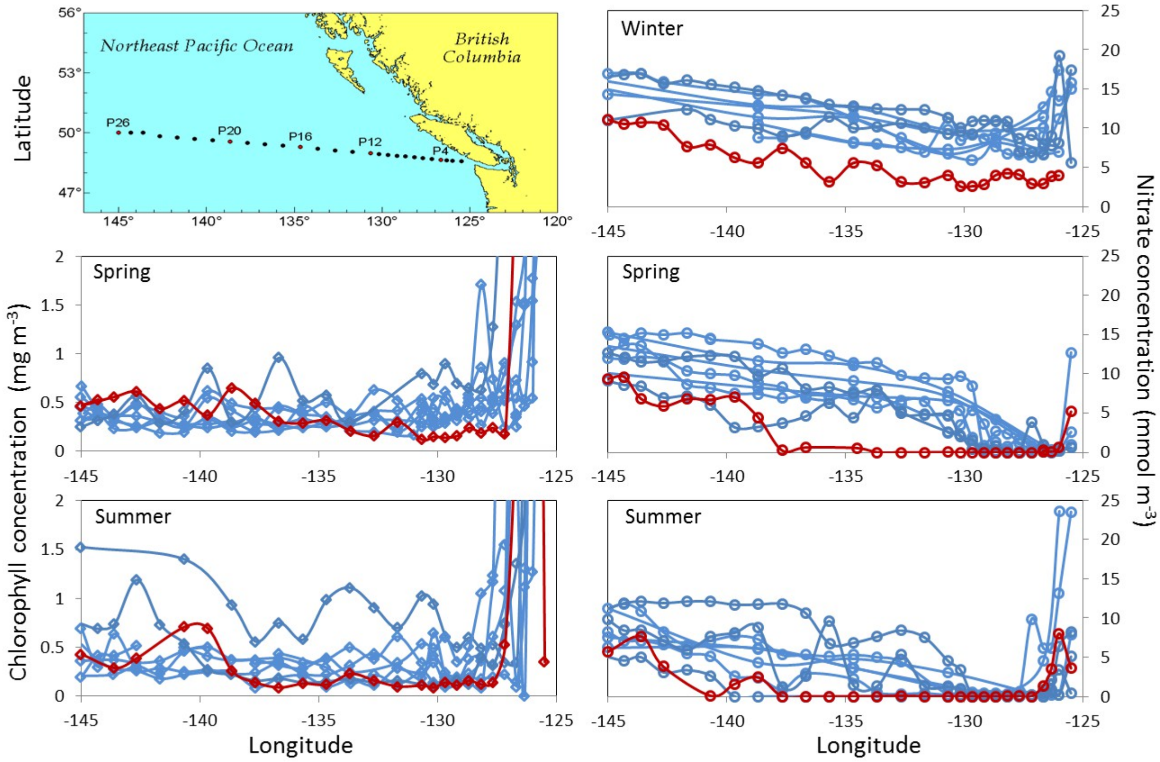


Figure 21: Location of sampling stations, chlorophyll-a (mg/m^3) and nitrate (mmol/m^3) in surface waters along Line P in winter, spring and summer of 2015 (red symbols) and 2008-2014 (blue symbols). Source: Chandler et al. (2016).

5. Sea level pressure (SLP)

Storms crossing the salmosphere tend to move as large-scale cyclones (counterclockwise) that travel from west to east. The intensity of a storm is related to the magnitude of the depression in atmospheric pressure at the sea surface. The effect on the ocean is generally strongest in fall and winter and the overall annual effect will depend on the frequency of storms, their intensity, location, timing, etc. during the winter. There are various methods of quantifying storminess and most of them are calculated from a monthly average sea level pressure grid derived from some type of global analysis such as the NOAA NCEP/NCAR Reanalysis that covers the period from 1948-present (Kalnay et al,. 1996). Neither 2015 nor 2016 winters (December-February) were extrema, but 2016 was the 3rd largest since 1948, which is not unexpected as winters during major el Niño events are generally among the most stormy (Emery and Hamilton 1985). During 2015, SLP extrema were both high and low. There were no low SLP extrema during the winter of 2015, but there were many during the summer and fall months (Figure 22). The low pressure extrema

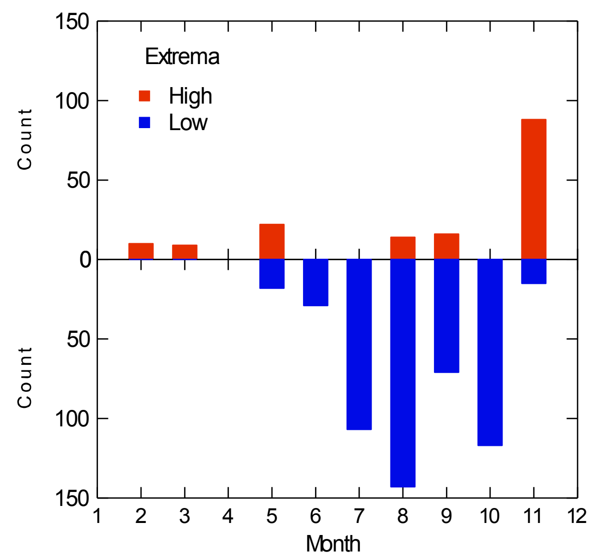


Figure 22: Number of 2.5° by 2.5° latitude/longitude grid points where sea level pressure extrema occurred in 2015 in the salmosphere.

were part of a widespread region in the subtropical North Pacific, centred approximately at Hawaii but extending northeastward to British Columbia and westward past the International Date Line (Figure 23). The few high SLP anomalies during this period were in the Bering Sea. As the mean SLP gradient in the North Pacific has a trend from high in the southeastern region to low in the northwest in summer, the summer and fall of 2015 featured a much reduced gradient which tends to reduce winds. The high SLP extrema in 2015 occurred primarily in November (Figure 23). The extrema were part of a widespread pattern of high SLP anomalies across the southern salmosphere (Figure 24). There were no SAT anomalies associated with this pattern.

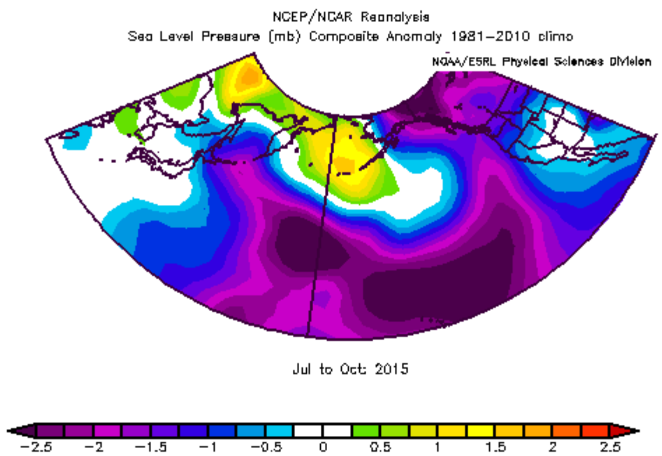


Figure 23: Average SLP anomalies from July to October, 2015.

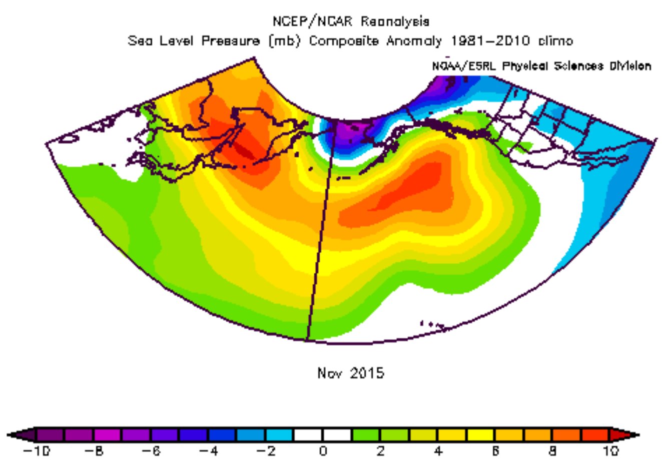


Figure 24: SLP anomalies during the month of November, 2015.

6. Chlorophyll

Phytoplankton are single celled organisms in the sea that combine energy from the sun (light) and nutrients drawn from seawater to store that energy in chemical bonds via photosynthesis. This energy is made available to animals if they consume and digest the phytoplankton. The quantities of light and nutrients determine how much energy is captured and stored at the base of the food web. Various factors influence the availability of sunlight and nutrients to phytoplankton, thereby affecting the availability of energy to herbivores and omnivores. As all have evolved together, strategies have developed among consumers to take advantage of this stored energy when and where it is available. Occasionally, the norm is substantially disrupted, and depending upon the nature of the disruption, can lead to the benefit or the detriment of consumers. One of the major disruptions involves variations in seasonal timing (Hjort 1914) and the study of this variation is known as phenology. This section of the report examines variations in the seasonal development of phytoplankton in the Northeast Pacific region of the salmosphere.

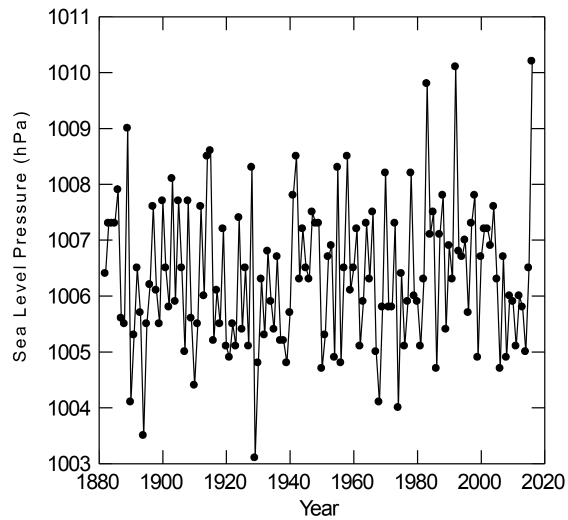


Figure 25: Sea level pressure (hectopascals) at Darwin, Australia during the month of January from 1882-2016. The highest SLP occurred in 2016, 1992, and 1983 (el Niño years) Source: http://www.cpc.ncep.noaa.gov/data/indices/

Chlorophyll concentrations in seawater are generally obtained by one of two methods: *in situ* water samples, or remotely via satellite measurements of ocean colour and generally, there is good correspondence between the two methods. In the Northeast Pacific, chlorophyll concentrations measured by ocean colour sensors on satellites (eg. SeaWiFS, MERIS, MODIS-A) indicate that the coastal zone has much higher chlorophyll concentrations than the deep water regions.

6.1. Shipboard sampling

Twice monthly *in situ* sampling at Station NH-15 in 2015 off the Oregon/Washington coast identified the onset and evolution of a widespread *Pseudo-nitzschia* algal bloom along the North American coast (Du et al. 2016). Its toxicity (they can produce a toxin; domoic acid) resulted the closure of the razor clam fishery and and first ever closure in the region of the Dungeness crab harvest. Domoic acid was transferred via the food web (sardine/anchovy) to higher trophic levels with deathly consequences for seabirds and marine mammals (Du et al. 2016). In British Columbia, high chlorophyll *a* concentrations were observed during sampling off the west coast of Vancouver Island in July 2015 (Chandler et al. 2016). *Pseudo-nitzschia fraudulenta*, a potential source of domoic acid represented 32% of all diatoms sampled and fishery closures were far fewer than in Washington/Oregon.

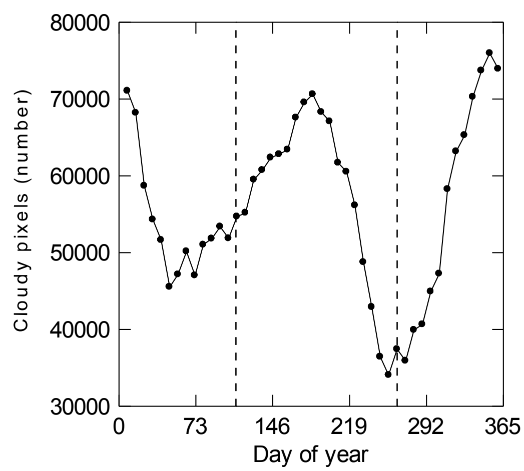


Figure 26: Annual cycle of numbers of non-visible pixels (clouds or insufficient light) in the salmosphere (East of 165°W based on counts of missing pixels in the MODIS-A ocean colour satellite (2002-present) summarized to an 8-day 9 km² grid. Late winter and the fall equinox provide the clearest views.

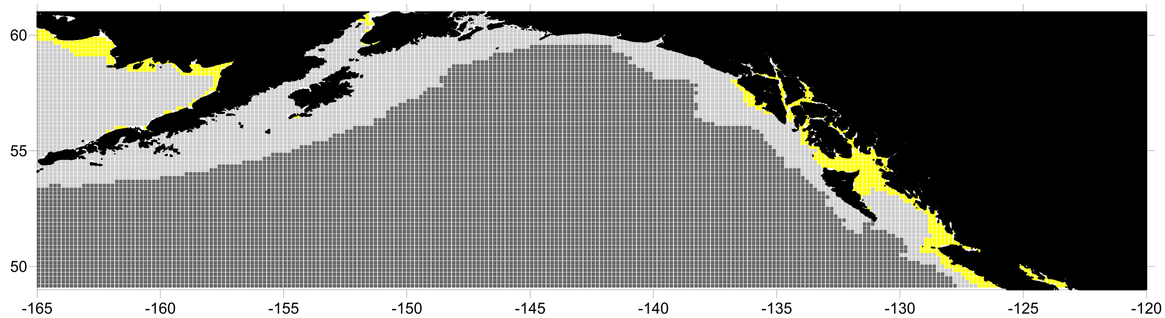


Figure 27: Cluster analysis of chlorophyll concentration time series (2002-2016) reveals coastal (yellow), shelf (light gray) and offshore (dark grey regions. Differences in seasonal cycles between regions are portrayed in Figure 28.

6.2. Satellite chlorophyll

The ability to measure chlorophyll from satellites relies on sunlight and cloudless skies and their frequency of occurrence varies seasonally (Figure 26). To distinguish the regions, individual pixels (each representing 9 km^2 of ocean) were assigned group membership solely on the basis of their similarity to all other pixels during the period 2002-2016, regardless of where they were located. Similarity between pixels was based on sum-of-squared differences of the 8-daily concentrations across all years. The groups formed by cluster analysis created an intuitive division into what appear to be coastal, shelf, and offshore zones (Figure 27). The coastal zone includes what is often called the Inside Passage, including also the West coast of Vancouver Is. and the east side of Bristol Bay.

The shelf zone extends beyond the continental shelf and forms a transition region between offshore and coastal zones except in the northern Gulf of Alaska and the Alaska Peninsula (both sides) where it extends to the land. The offshore region is clearly situated over the deep waters of the Gulf of Alaska. Zones can be distinguished by their average levels, by their variance, and by the relative magnitudes of their seasonal peaks (Figure 28).

a) Coastal

The coastal zone has a prominent spring bloom with a relatively weak fall bloom (Figure 28) and generally higher chlorophyll concentrations throughout the year than the other zones. In 2015, extrema in chlorophyll concentration occurred during a 7 week period from mid-February to the end of March and again in June (Figure 30). A bloom occurring in winter was unusual in this record when compared to other years (Figure 29). See Figure 31 and Figure 32 for a comparison of high and low chlorophyll winters. The anomalous winter bloom in 205 also featured as a precursor to the Oregon/Washington bloom with the toxic alga, *Pseudo-nitzschia* (Du et al. 2016). By the end of summer in 2015, chlorophyll extrema in the other direction (low) appeared during a week ending in mid-September and two week period during October (Figure 30).

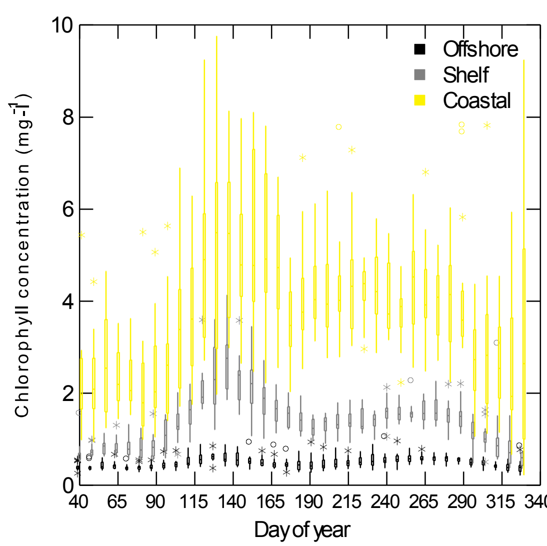


Figure 28: Average 8-daily chlorophyll concentrations by region within the salmosphere. Regions (Figure 27) are coastal (yellow), shelf (gray), and offshore (black).

b) Shelf

The shelf zone has lower average chlorophyll than the coastal zone and its seasonal characteristics are intermediate between that of the coastal zone and that found in the offshore (Figure 28). In 2015, it also exhibited atypically high chlorophyll concentrations in February-March of 2015 (blue line on the left in Figure 30).

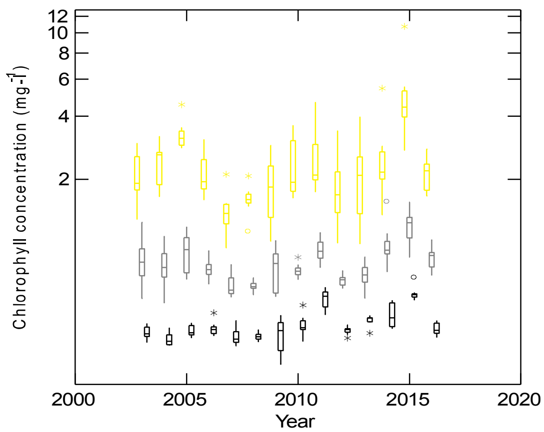


Figure 29: By region and year, box and whisker plots of average chlorophyll concentrations during only the 8-day periods of extreme anomalies in 2015 (February -March). The median value was highest in 2015 in all 3 regions with the largest anomaly in the coastal zone adjacent to coastlines. Regions coloured as in Figure 28.

c) Offshore

The offshore region has much lower average chlorophyll concentrations than the coastal region and lacks a dominant spring bloom so the spring and fall blooms are of approximately the same magnitude (Figure 26). Analysis of offshore chlorophyll anomalies was restricted to satellite data for the eastern salmosphere in the North Pacific (east of 165° W) which also includes a portion of the southeastern Bering Sea. The seasonal cycle of chlorophyll concentrations is relatively weak (Thomas et al. 2012). Nevertheless, despite its low amplitude, an annual cycle with spring and fall peaks is evident. Higher average chlorophyll occurs during winter (January-April) and fall (October-November) and lower average chlorophyll during the summer (June-August) with rapid transitions between seasons in May and September. Low summer chlorophyll values are due to zooplankton grazing (McAllister et al. 1960) but summer is also a period of extensive cloud cover . The least cloud cover occurs just before the equinox in spring and at the equinox in fall (Figure 24).

As had occurred in the coastal region in 2015, lesser chlorophyll extrema also occurred in the offshore region in early February and through most of March (Figure 30). Unlike the coastal region, however, the offshore region had positive extrema in October 2015. A strong fall bloom may have occurred because of the oncoming of an el Niño winter when Gulf of Alaska winds tend to be stronger than average in the winter, but perhaps not as early as October. Following two years of a marine heat wave (di Lorenzo and Mantua 2016), the mixed layer was relatively shallow with high concentrations of nutrients stored beneath the mixed layer. The nutrients would be released (mixed to the surface waters) by vertical mixing when the autumnal winds arrived and because of the nutrient gradient with depth, more nutrients may be available if the winds are stronger than average.

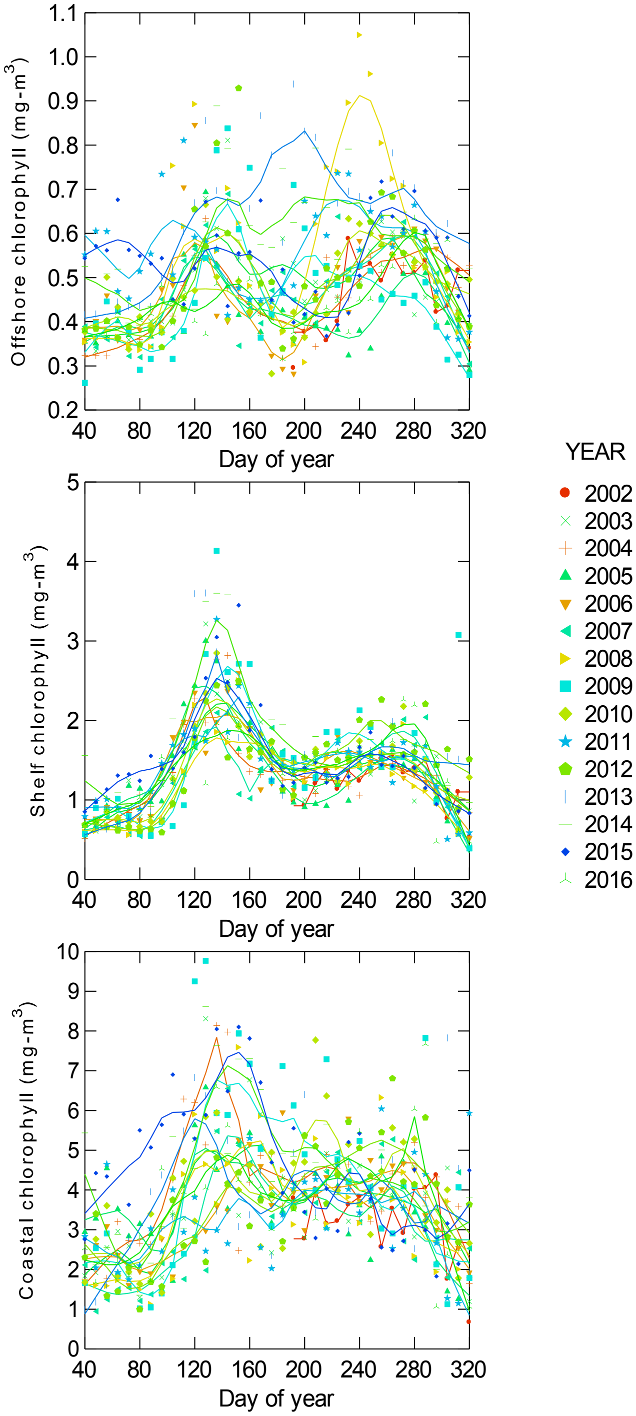


Figure 30: Lowess smoother applied zone-wide average chlorophyll concentrations by year in 3 regions: Offshore, Shelf, Coastal. In each region, the line for 2015 (blue) begins above that for the other years. Higher than average chlorophyll offshore later in 2008 (top panel) is the Kasatochi volcano effect while the origin of the 2013 summer peak there is not known.

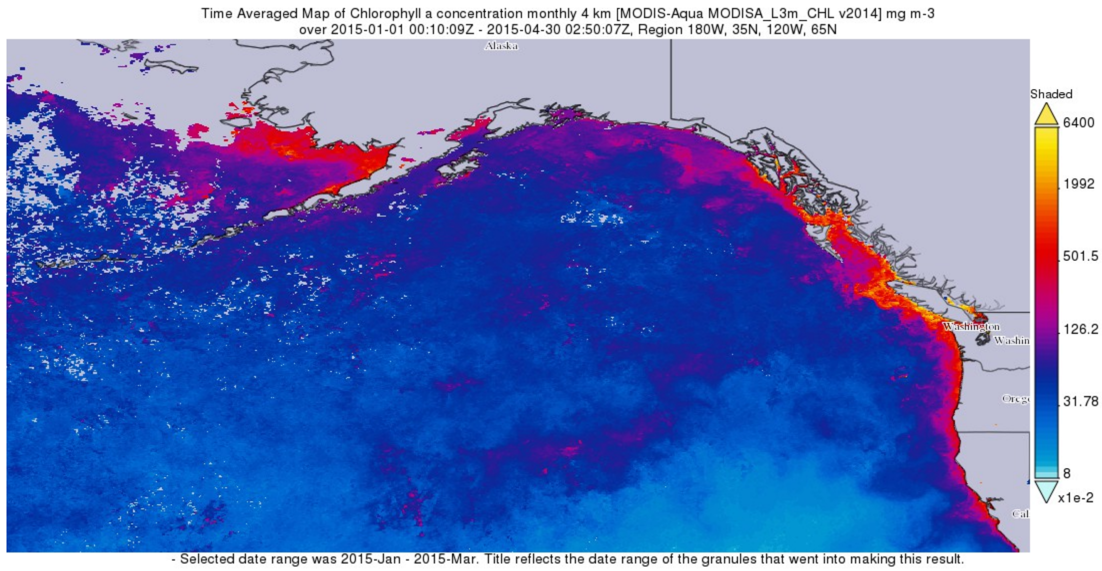


Figure 31: Chlorophyll concentration in the Northeast Pacific in winter (Jan-Apr) of 2015.

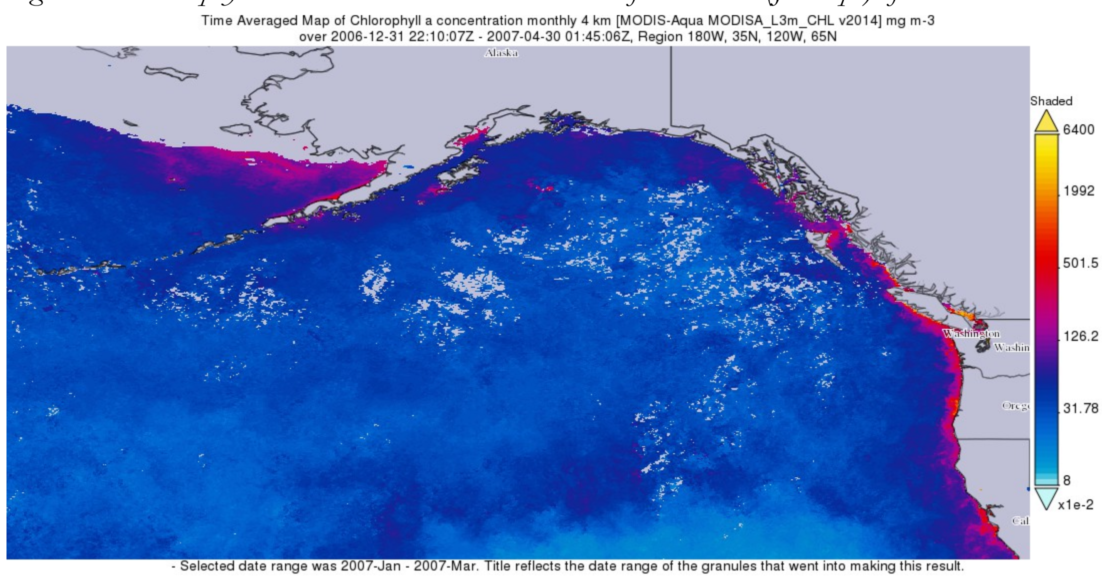


Figure 32: Chlorophyll concentration in the Northeast Pacific in winter (Jan-Apr) of 2007.

6.3. Chlorophyll phenology

Phenology in the eastern salmosphere was examined by evaluating the seasonal development of chlorophyll in each of 3 zones identified above. To increase the spatial coverage within each 8-daily period and to fill in gaps found at individual pixels, average chlorophyll concentrations were calculated on a 1° x 1° grid from the basic 9 km^2 resolution, for each year and 8-day period. If no data were available due to low light (December-January), the time series was shortened by a few weeks at each end. Timing was evaluated by fitting curves to the cumulative chlorophyll concentration at each grid point, seeking points of inflection during a year where chlorophyll was most rapidly increasing. Initially a single curve (single peak) was fit to each time series, but if there was a substantial improvement in the fit (R^2 increase >5%) by entertaining two seasonal peaks, spring and fall, then this result was adopted. The "fall" peak may be a misnomer here as the second peak found by the algorithm was typically in the fall (Figure 28) but may have occurred earlier.

a) Offshore

Most of the grid points exhibited evidence (improvement in R^2) of weak spring and fall chlorophyll peaks. The peak day of year of spring chlorophyll concentration in the offshore is highly variable, which is not too surprising given that it is a region known for little or no evidence of a bloom. Box and whisker plots were used to indicate, across the zone, where the peak dates were concentrated in each season (Figure 31). Within the zone, the timing peaks were more or less concentrated near a median date depending on year. There was no outstanding shift in median spring timing or extrema in 2015, however, there is an extremum (late) in median date of the fall bloom in 2016.

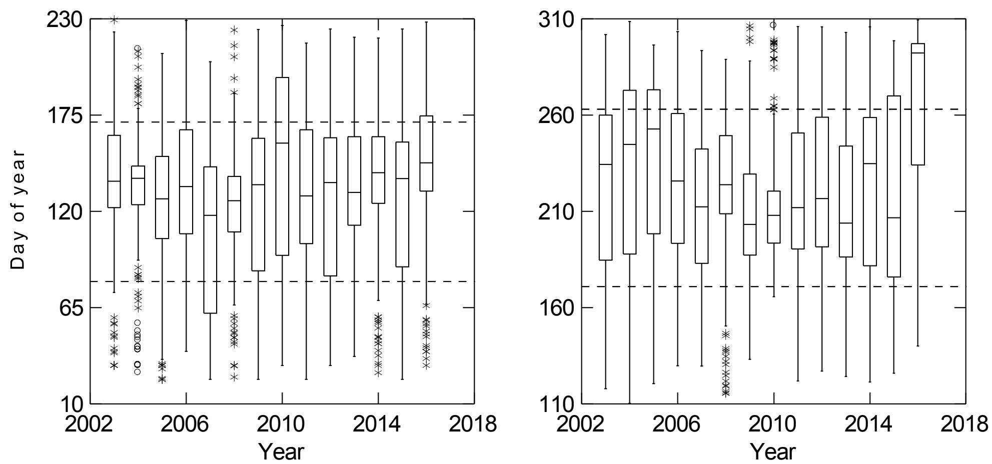


*Figure 33: Box and whisker plots of peak spring (left) and peak fall (right) chlorophyll concentration offshore (east of 165° W estimated by curve fitting. Each dot represents 1 grid point in 1 year. The dates of the equinoxes and summer solstice are indicated as dashed lines to provide a seasonal timing reference.. * indicate timing that was an outlier (within that year).*

b) Shelf

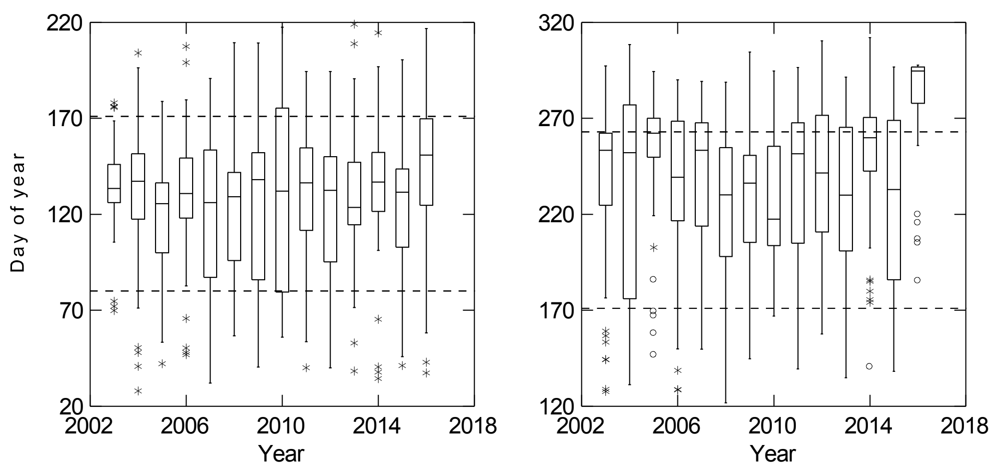


*Figure 34: Box and whisker plots of peak spring (left) and peak fall (right) chlorophyll concentration in the shelf region (east of 165°W) estimated by curve fitting. Each dot represents 1 grid point in 1 year. The dates of the equinoxes and summer solstice are indicated as dashed lines. * indicate timing that was an outlier (within that year) at a grid point.*

As in the offshore region, median peak date of bloom timing in the shelf region was an extremum (late) in 2016 in fall, but also had a late median date in spring (Figure 32). As this is somewhat of a transition between the nearshore and offshore, it is not too surprising that it picks up some of the characteristics of each. This region is expected to have additional variability because of the relatively greater influence of mesoscale eddy activity (Brickley and Thomas 2004; Crawford et al. 2005; Ladd 2007). To date, the role of eddies in salmon biology is not well known. For the most part, studies have focused on their role in affecting migration timing (Hamilton and Mysak 1986; Hamilton et al. 2000).

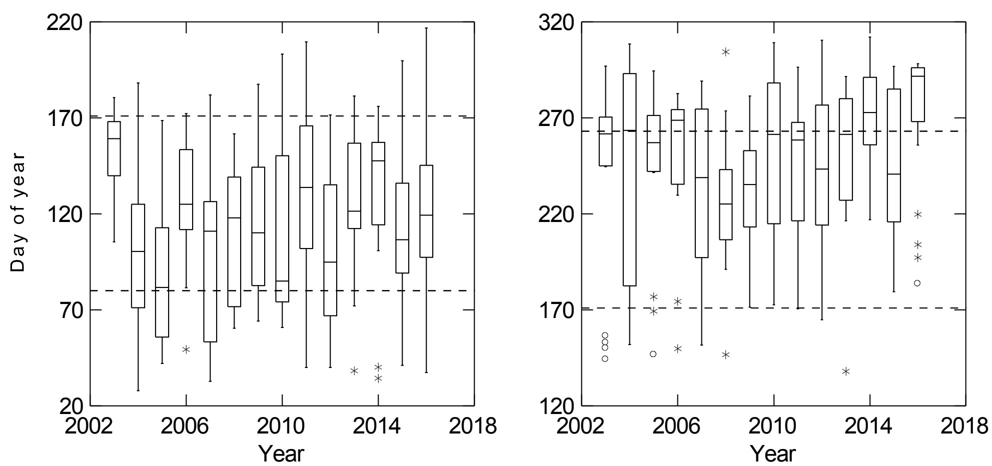


*Figure 35: Box and whisker plots of peak spring (left) and peak fall (right) chlorophyll concentration offshore (east of 165°W) estimated by curve fitting. Each dot represents 1 grid point in 1 year. The dates of the equinoxes and summer solstice are indicated as dashed lines. * indicate timing that was an outlier (within that year) at a grid point.*

c) Coastal

Median peak date in the coastal region was latest in 2003 and earliest in 2010 (Figure 33). The variability, measured by the lengths of whiskers, was greatest in 2016. The fall bloom was latest in 2016 and earliest in2008, a relatively cool year that was associated with an abundant return of Fraser River sockeye salmon but that may simply be a coincidence. Based on the previous analysis of coastal chlorophyll, there was an expectation that 2015 would have the earliest spring median date but that did not appear. There is a possibility that 2015 should have been modelled as a year of three peaks; a small but anomalous peak in winter, with normally timed spring and fall peaks. The early winter peak was probably swamped by the spring peak in a two-peak model.

6.4. Zooplankton

a) Coast/shelf

The current paradigm for juvenile salmon survival along the southeastern coast of the Gulf of Alaska is that survival is associated with the movement of different water masses along the North American coast making the environment more or less favourable for survival. A cooler (warmer) ocean in the south (north) is generally better (worse) for survival than a warmer (cooler) ocean (Mueter et al. 2002). Since the 1950s, dramatic changes in zooplankton communities have been observed regularly along the British Columbia, Washington, Oregon coastline (Beklemishev and Lybny-Gertsyk 1959; Frolander, 1962; Cross and Small 1967; Mackas 1984; Fulton and Lebrasseur 1985, Mackas et al. 2001, Mackas et al. 2007, Keister et al. 2010). The taxonomic composition of the zooplankton community (primarily copepods) and its total biomass can change abruptly (Frolander 1962).

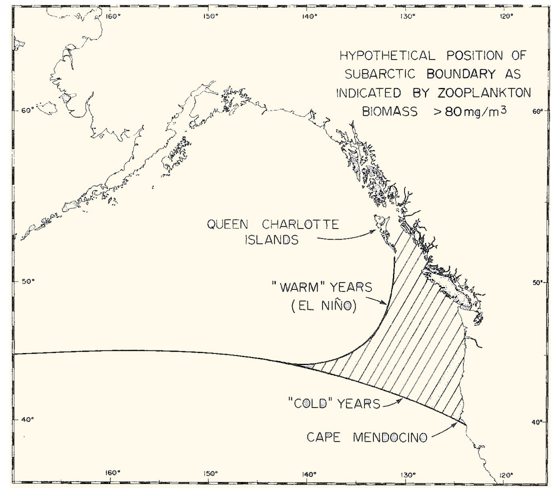


Figure 36: Schematic of variation of the copepod biomass in association with variation in ocean circulation. Source: Fulton and Lebrasseur (1985).

- Oregon

Regular and frequent sampling has shown the predominant role of low frequency variation in the coastal ocean since the late 20th century (Figure 37). Peterson classified the major differences as southern and northern communities. Their phasing implies a strong association with large-scale oceanographic features involving currents, water masses. It is also a region of strong upwelling but the dominant pattern in these time series is not the seasonal scale. The southern community is dominated by copepod taxa that do not store lipids and reproduction is continuous providing that adequate food is available. The northern community is dominated by large lipid-storing copepods that enter diapause after the spring feeding season with sufficient energy stored to survive to reproduce the following spring. The current paradigm is that the latter provide an enriched food web for juvenile Pacific salmon. At Newport, the southern community has prevailed since mid-2014 with the largest anomaly occurring in 2015 (data for 2016 were not available). Qualitatively, these strength of these anomalies does not look particularly different from similar periods in the past (Figure 37).

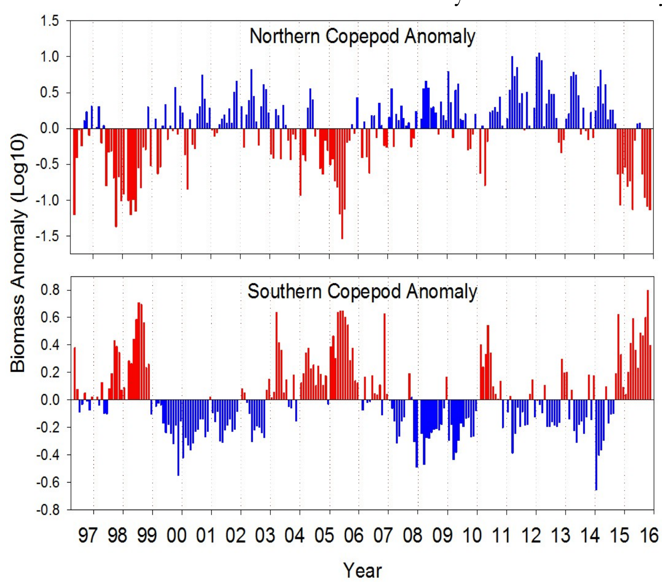


Figure 37: (W.T. Peterson's) biweekly zooplankton community composition off Newport, OR indicates variation in biomass of boreal versus subtropical copepod species. Source: https://www.nwfsc.noaa.gov/research/divisions/fe/estuarine/oeip/eb-copepod-anomalies.cfm#NSC-01

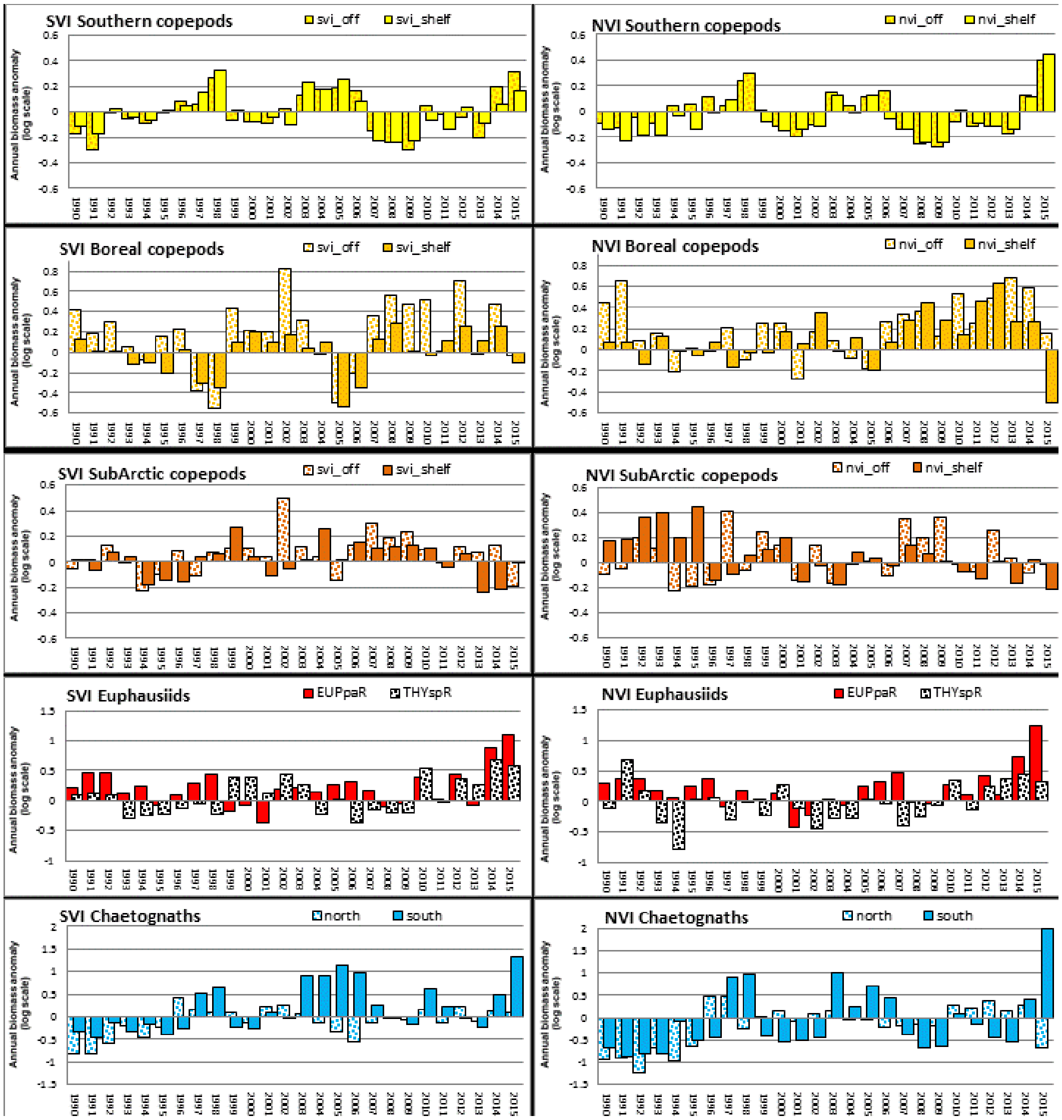


Figure 38: Zooplankton species-group anomaly time series (vs climatological baseline) for southwestern Vancouver Is. (left) and northwestern Vancouver Is. (right) regions. Ordinate is annual log scale anomalies. R in Euphausiids represents: corrected for day/night tows. EUPpa: Euphausia pacifica; THYsp: Thysanoessa spinifera; CHAET; Chaetognaths divided into north/south species group. Source: Chandler et al. 2016.

- West Coast Vancouver Island

A sufficiently large-scale climate event can affect the zooplankton communities in a similar way along much of the North American coastline (Mackas et al. 2006). Extrema in 2015 were widespread among many taxa along the Vancouver Is. coastline but were more extreme along its northwestern coast (Figure 38). This effect could have arisen from a stronger or more prominent poleward circulation of southern waters, creating stronger anomalies in the north. Southern latitudes along Vancouver Is. experience zooplankton anomalies regularly, in association el Niños (Fulton and LeBrasseur 1985) so the appearance of southern taxa and diminished northern taxa is not as unusual. Adult salmon returns in southern British Columbia, following zooplankton anomalies such as these, will tend to be poorer rather than better.

a) Offshore

- Continuous Plankton Recorder

Data for the NE Oceanic Region (a CPR-defined region) were made available by the Director of CPR-Pacific as final results for 2015 and preliminary results for 2016 (to July). Preliminary results are based on 25% of a normal annual sample size for the program. 2015- no extrema were found in the zooplankton samples taken in the Oceanic Region (eastern Gulf of Alaska) during the CPR survey (Figure 39).

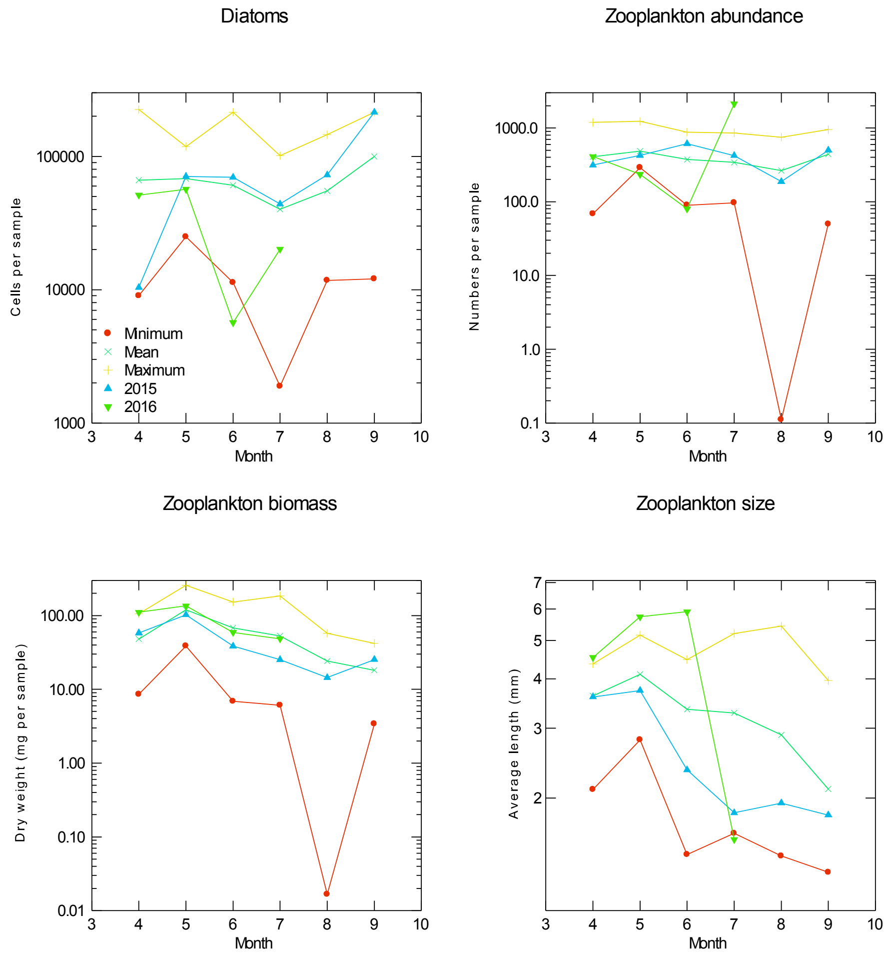


Figure 39: Indices of high seas plankton community based on Continuous Plankton Recorder data (courtesy of Dr. Sonia Batten, Director, CPR - Pacific). Statistics are based on 2000-2015 average monthly values. Colour legend for all panels appears in the top left panel. All ordinates are log-scale. Data for 2016 are available only to July. Minimum, maximum and mean statistics are based on data from 2000-2015 so extrema in 2016 can exceed the minimum and maximum.

Salmon Extrema

Bering Sea

<u>Yukon River</u>

- Eagle - Since 2005, the counts of chinook salmon at Eagle in 2015 was an extremum (high) and the return timing in 2016 was an extremum (early). In contrast to the early return of chinook salmon in 2016, the extrema (since 2006) for fall chum in 2016 was the most skewed return and latest peak.
- Anvik - The summer run of chum at Anvik R. (since 1980) was the most skewed (slow rise to a peak), but the date of the peak was not an extremum. Even year pink salmon had the latest peak date (since 1994) in 2016.

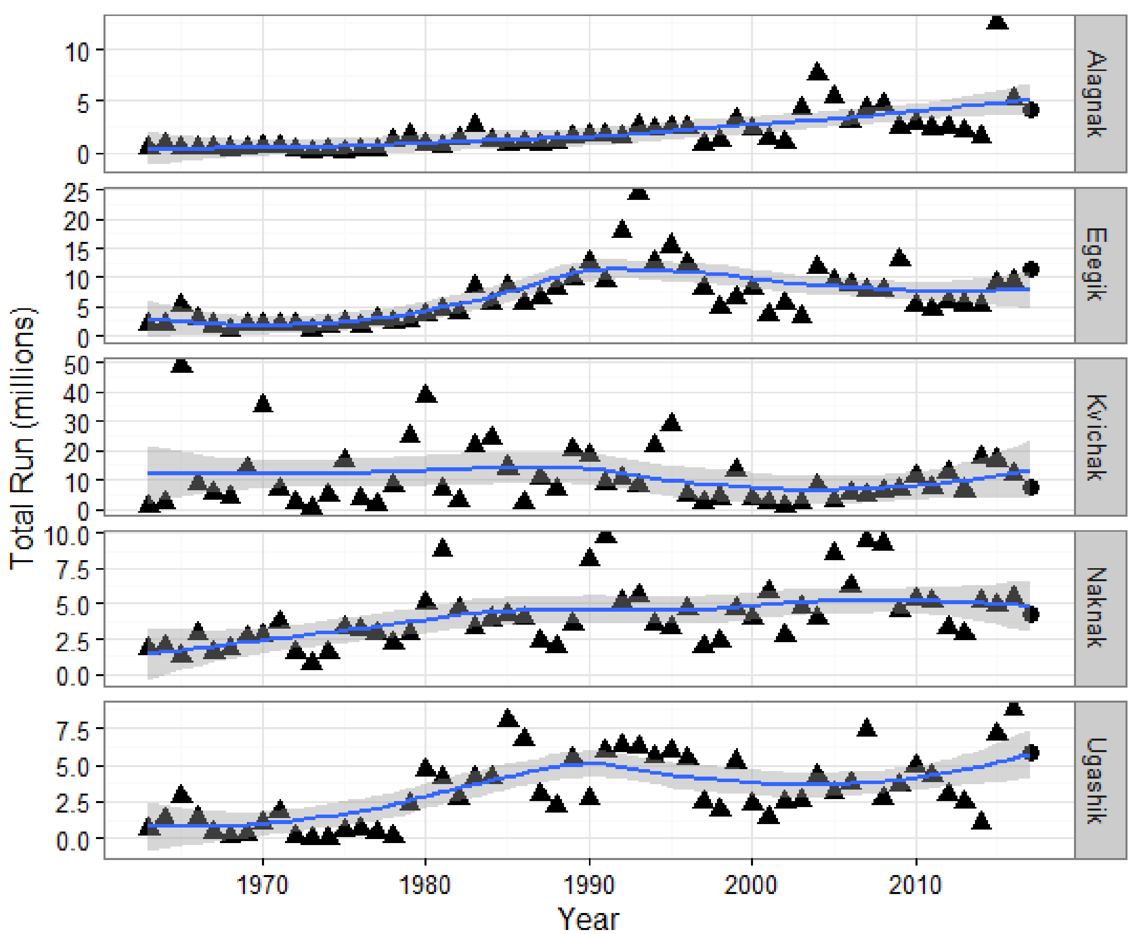


Figure 40: Total returns of sockeye salmon to east side rivers in Bristol Bay 2016 and forecast for 2017 (solid circle). Source: http://www.adfg.alaska.gov/static/applications/dcfnewsrelease/756093217.pdf

<u>Bristol Bay</u>

- anomalies in the sockeye salmon return recently have been in timing rather than abundance. For example, 2015 was the latest return of sockeye salmon past the Port Moller test fishery, in contrast to 2013 which was the earliest return on record. An abundance extrema (positive) occurred in the

Alagnak R. in 2015 and the Ugashik R. in 2016 (Figure 40). No other total return extrema occurred in other rivers in either year. There were no abundance extrema in 2015 or 2016 in west side rivers (Figure 41).

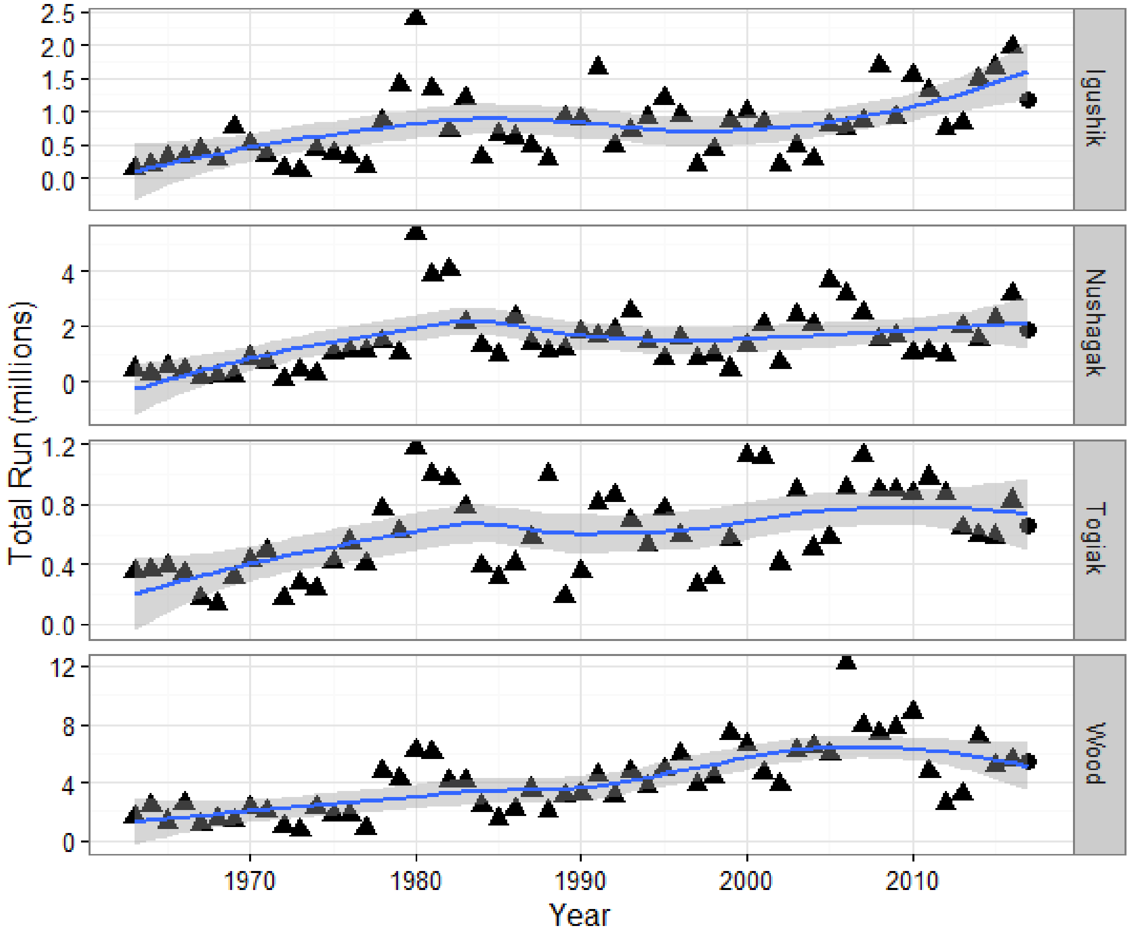


Figure 41: Total returns of sockeye salmon to west side rivers in Bristol Bay 2016 and forecast for 2017 (solid circle). Source: http://www.adfg.alaska.gov/static/applications/dcfnewsrelease/756093217.pdf

Northern Gulf of Alaska

Copper River

- Coho salmon commercial harvest was the largest since 2004.
- Chinook and sockeye salmon runs in 2016 were bad and average, respectively.
- Mean size of sockeye salmon (without regard to age) was an extremum (small) in 2015 (Source: http://www.alaskajournal.com/2016-05-26/recent-trend-small-sockeye-continues-copper-river)
- The early-run sockeye salmon abundance was an extremum in 2015 but no other timing/abundance anomalies were found for this species.

Kodiak

- In 2016, pink salmon harvest was the lowest since the 1970s. (Source: http://www.adfg.alaska.gov/index.cfm?adfg=commercialbyfisherysalmon.bluesheetsummary). The pink salmon run to the Karluk R. was front loaded (most arriving early but without a peak date extremum) with a protracted finish.

- The abundance of the early-run sockeye salmon to the Karluk River in 2015 was an extremum (high) as was the late-run abundance in 2016.
-

Russian River (Cook Inlet)

- Sockeye salmon had no anomalies in 2015 but the return of early-run sockeye salmon in 2016 was the least compressed in the record.
- Chinook salmon had no extrema in 2015, but in 2016 was the earliest found and the run timing shape was front loaded.

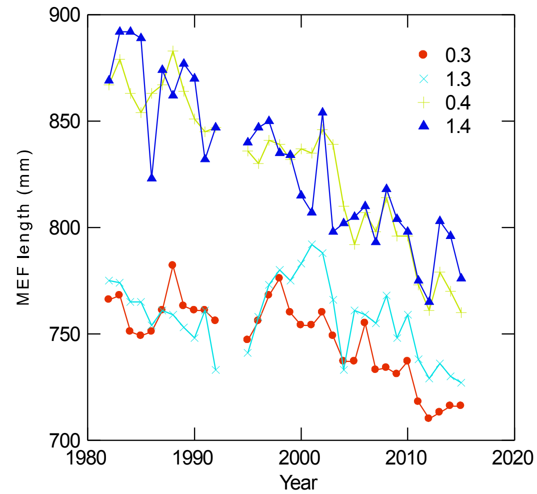


Figure 42: Mean mid-eye to fork (MEF) length (mm) of 4 age-classes of chinook salmon in the SEAK troll fishery during statistical weeks 27-29. Data courtesy of L. Shaul, ADFG.

Southeast Alaska

Chinook summer troll fishery

Although the mean length of age 1.3 and age 0.4 chinook salmon in the summer (statistical weeks 27-29) troll fishery was the smallest in the record in 2015, the dominant feature of temporal change is the overall decline during the past 35 years (Figure 42). The rate of decrease increases with ocean age.

Pink salmon

Forecasts of pink salmon harvests in Southeast Alaska based on juvenile pink salmon abundances in Icy Strait the previous year are relatively reliable in most years (Figure 43); 2015 and 2016 are noteworthy negative anomalies but not extrema. In 2016, harvests of pink salmon in Southeast Alaska were approximately 18 million whereas 30 million was the forecast based on a juvenile index value of 2.2. Harvests in 2015 were well below forecast. The annual mean weight of pink salmon caught in northern SEAK and southern SEAK fisheries is highly correlated (r = 0.9) suggesting that they share common growing conditions in the Gulf of Alaska. There were no body size extrema in 2015 or 2016.

Sockeye salmon

Time series of mean length of age 1.2 and age 1.3 sockeye salmon were available from Hugh Smith Lake, McDonald Lake, Ford Arm Lake, Situk Lake, and Chilkoot Lake. A principal component analysis of mean length of 10 age/population combinations indicated that they share only 43% of covariation in common but all load positively on the leading PC. The shared component is much lower than for SEAK pink salmon mean weight. The subdominant PC distinguished age 1.2 fish from age 1.3 fish. In northern BC sockeye populations, these two age-classes tend to occupy different locations in the Gulf of

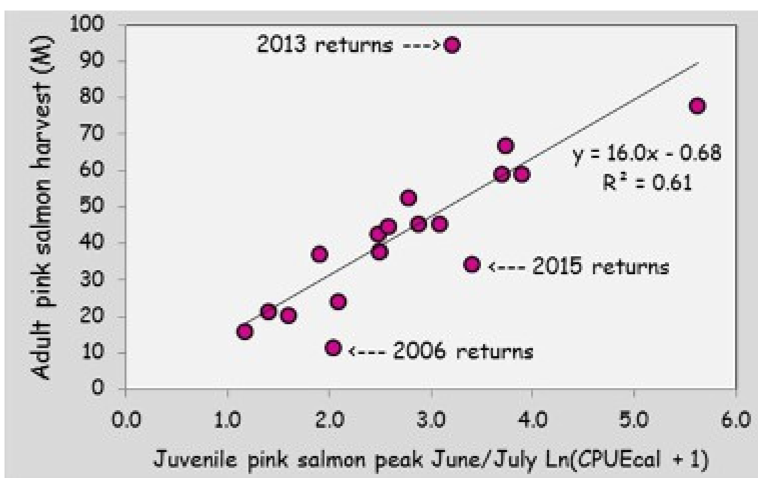


Figure 43: Correlation of juvenile pink salmon peak CPUE in Icy Strait (June or July) and SEAK adult pink harvest the following year. The observed value of the abscissa in 2015 was 2.2, implying a harvest in 2016 of ~30 million. Source: Orsi et al. (NOAA/ABL)

Alaska (McKinnell 1995). Only Chilkoot R. (age 1.3) had a mean length extremum (small) in 2015. Some sites (McDonald L.) was not sampled in 2015 and 2016, nor was Ford Arm Lake in 2016. Data for Situk L. for 2016 were not available at the time of writing but will be later, so mean length was interpolated (L. Shaul, ADFG, pers. comm.).

Coho salmon
Average dressed weight data are available from the coho troll fishery from the 1970s. There were no extrema in mean weight in 2015 (2016 not available). The mean length of coho salmon spawners has declined generally over the past 35 years (Figure 44) although the past year or two has seen increases above the recent average in 3 of 4 of these populations. There were no extrema in mean length in 2015 or 2016 in these populations.

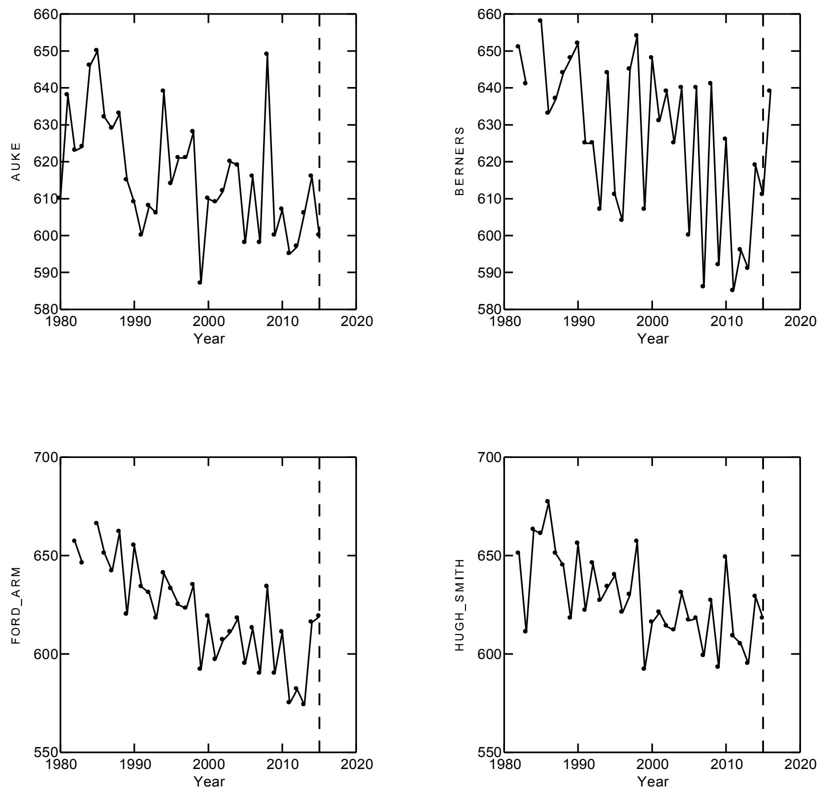


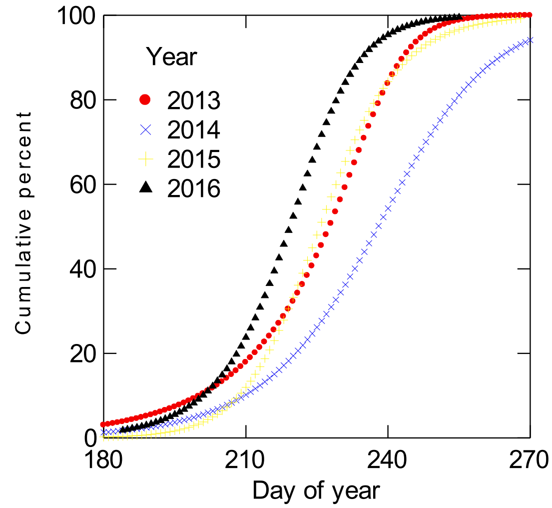
Figure 44: Mean length of coho salmon spawners (male and female average) at four locations in Southeast Alaska: Auke Creek, Berners River, Ford Arm Lake, and Hugh Smith Lake. Data courtesy of L. Shaul, ADFG.The dashed vertical line indicates 2015.

British Columbia

Nass River
Data collected at a fish wheel in the lower river since 1994. Sockeye salmon and chinook salmon are better described by two pulses of migration.

- 2015 - the abundances of early and late running sockeye and early and late running chinook salmon were extrema (low). There were no other extrema.

- 2016 – the abundances of early and late running sockeye and chinook salmon were extrema (high). The peak date of the early running sockeye salmon and the late running chinook salmon was an extremum (late) and the latter was very compressed (extremum). Coho salmon abundance was an extremum (low) and timing was early and brief (both extrema).



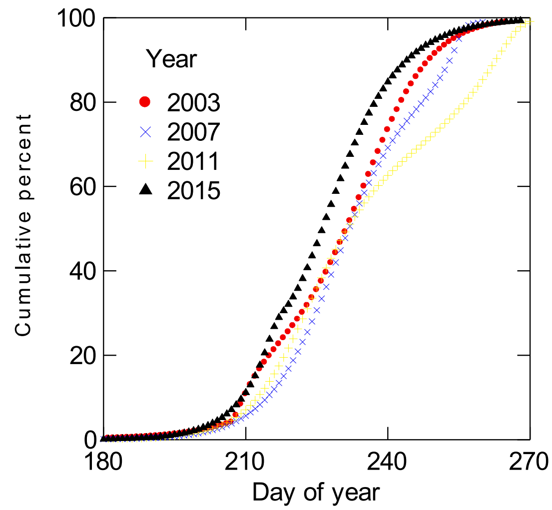


Figure 45: [upper] Single pulse fits to cumulative timing at the Whonnock test fishery (Fraser R.) from 2013 to 2016.[lower] Two pulse fits to the same test fishery by 2015 cycle year.

<u>Skeena River</u>

Data are from the Tyee gillnet test fishery in the lower river since 1956. The later running species (chum, coho) continue migrating after the test fishery closes so the data will only reflect catch-per-unit-effort until that date. The abundance extremum (low) for sockeye salmon occurred in 2013.

- 2015 - the return of chinook salmon was late and compressed. There were other extrema for any species.
- 2016 – the sockeye salmon run was late. There were no extrema in abundances or timings for any species.

<u>Long Lake</u>

The migration of sockeye salmon through Docee fence can, in most years, be described adequately by a single pulse of spawners passing through the fence. Infrequently, as in 2005, the migration has multiple pulses of spawners passing through the ladder and a single pulse model is inadequate. In 2016, the run was the earliest observed during the period from 1980. No other characteristics of the run were extreme in either 2015 or 2016, when the migration modelled as a single pulse.

<u>Strait of Georgia and WCVI</u>

The marine survival of coho salmon in the Strait of Georgia declined abruptly after the 1980s (Figure 46). For the last two decades, it has remained low; less than half of what occurs on the West coast. The last two decades are one continuous extremum.

<u>Fraser River</u>

The Fraser River approach route test fisheries for sockeye salmon and pink salmon in Johnstone Strait and the Strait of Juan de Fuca are both unique and valuable because they provide information on salmon timing, abundance, and size, prior to fishing, although years with later opening dates tend to miss the beginnings of early returning sockeye populations in the Upper Fraser, Baker Lake and Lake Washington. Other salmon species are caught as well although some are not on spawning migrations. For coho salmon and chum salmon these test fisheries are closed before spawning migrations of begin in earnest so catches may not necessarily be well described by a model that anticipates migration peaks. Nevertheless, the shapes of cumulative abundance curves provide an opportunity for comparison among years.

As any biologist or manager can attest, the migration of Fraser River sockeye salmon is complicated. Since 2002, and likely before that, there have been relatively consistent differences in timing/abundance curves for the total return among cycle years. The 2016 cycle, for example, is distinguished from other cycles because of its earlier average timing (Figure 45, upper panel), which is caused for the most part by low average abundance in the late run populations. Therefore, in not dealing with stock-specific timing curves, anomalies should be calculated with respect to this four year cycle. However, with the available data, the number of years available to compute an average for any cycle year is only three or four. Furthermore, because there are so many populations, some of remarkable abundance, interannual variations in their relative abundances can easily affect the characteristics of any annual timing curve. Added to this source of variability are the effects of differences among test fisheries in their ability to detect the abundance signal, plus variable start and end dates.

Given the numbers of species×ages involved (8), the numbers of test fisheries (5), and variations in patterns among years, only single pulse models were fit to each, but there are clearly some years and species where multiple pulses would markedly improve the fit. In general, a single pulse model accounts for >50% of the variation in CPUE (e.g. > 70% in the San Juan seine test fishery) but there are also some years and species with misfits ($R^2<10\%$) but they do not occur often. Example of fitting multi-pulse models is seen in Figure 47 (sockeye) and Figure 49 (pink) compared to a single pulse in Figure 45.

The most remarkable migration timing anomaly in Fraser River sockeye salmon in recent memory occurred in 2005 (2013 cycle), a year of many remarkable environmental and biological extremes (see special issue on this event in Geophysical Research Letters Vol. 33) and subsequently low abundances of adult Fraser River sockeye salmon in 2007. Indeed, 2005 was so unusual that even greater timing extrema are almost unimaginable without digging into the distant past for a reminder.[3]

Sockeye salmon

- 2015
    - Regardless of whether a single pulse or multi-pulse migration model was used, the sockeye salmon return timing past the Whonnock test fishery (within the Fraser River) in 2015 had an intermediate timing when compared with four recent years, but it was generally earlier than the other years on that cycle (Figure 45). Early timing in a warm year is inconsistent with the "cold early-warm late" pattern that has been relatively consistent through the last half century (Blackburn 1987, McKinnell et al. 2012). In that sense, 2015 was an extremum because a later than average return would have been expected based on the coastal heatwave of that year. On the other hand, DFO had forecast an early return of Summer-run stocks (Fraser R. panel news release of 2015). Subsequent news releases noted the Early Summer and Summer runs were protracted as had occurred during the last heat-wave (McKinnell 2000).
    - There were no timing/abundance extrema for large sockeye salmon in 2015 at the Round Is. (gillnet) test fishery but the Blinkhorn Is. (seine) test fishery was the least compressed (protracted), as was noted in the in-season Fraser River Panel reports. In contrast to the Round Is. test fishery, the abundance of large sockeye salmon in the gillnet test fishery at San Juan was an extremum (low) in 2015. There were no sockeye salmon extrema in the San Juan seine

3 Peak catch of sockeye salmon in 1926, a major el Niño year, occurred during the week of October 2 (Clemens & Clemens 1927).

fishery in 2015.

- 2016
    - large sockeye salmon in the Round Is. test fishery were the earliest observed, which coincided with an extremum in skewness (peak early). Large sockeye salmon in the Blinkhorn test fishery were the earliest in the record. The early timing in a warm year is inconsistent with historical norms.
    - Small sockeye salmon (age 3_2) are not caught in the gillnet test fisheries as they are too small. Their abundance in 2016 was an extremum (low). In cycle years where larger average abundances of small sockeye are expected (2014 cycle), their abundance is an index of large sockeye salmon returns the following year (McKinnell et al. 2012) but it is not clear how well this index might work in years when average abundances are expected to be low. The low abundance extrema of small sockeye salmon that was observed in the Blinkhorn test fishery in 2016 was also observed in the San Juan seine test fishery.
    - There were no extrema in the San Juan gillnet test fishery in 2016, but the 2016 Blinkhorn test fishery had the most extreme abundance (low), skewness (early), compression (high), and peak date (early).

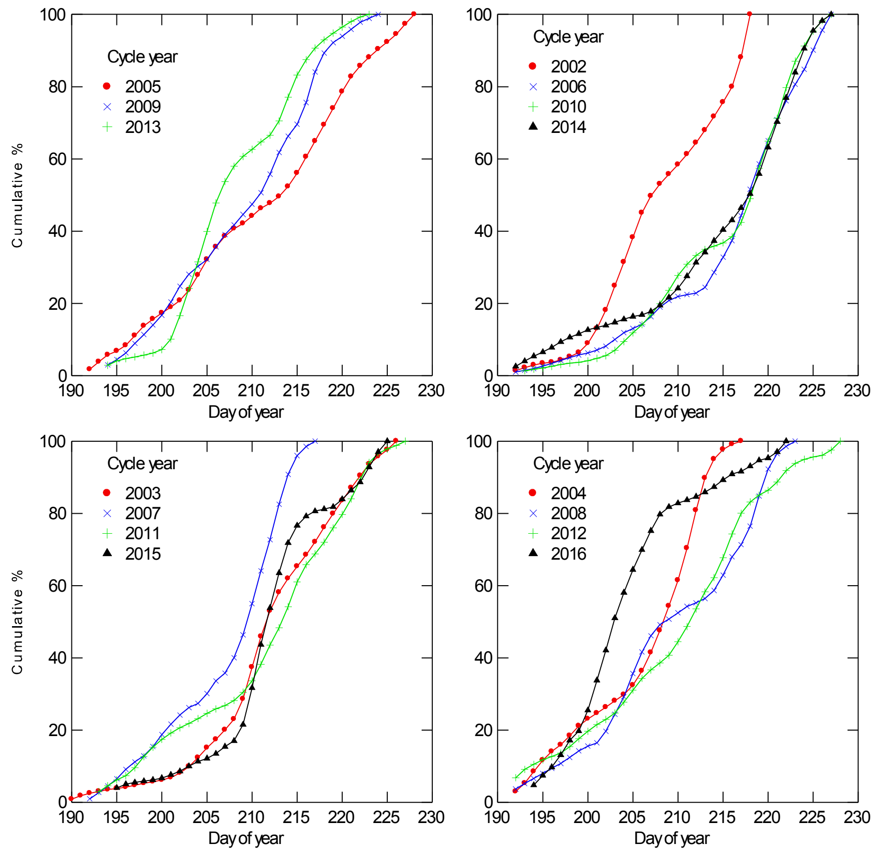


Figure 47: Large sockeye salmon catch in the Round Island gillnet test fishery (fit to a 3 pulse model rather than a 1 pulse model).

Pink salmon (2015 only)

- The body weight of Fraser River pink salmon has exhibited a long-term decline since 1950s (Figure 48). Although different sampling methods have been used to determine annual average weight, the average weight in 2015 was the lowest in the record. No equivalent body size extremum was found in Southeast Alaska even though historical tagging records indicate a common oceanic environment.

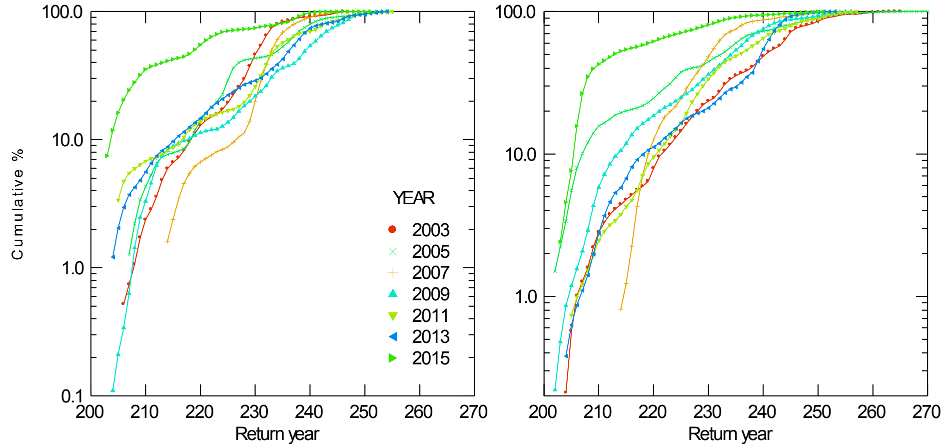


Figure 49: Cumulative CPUE of pink salmon (% of total) at San Juan (left) and Blinkhorn (right) test fisheries in odd years from 2003 to 2015.

- From 2002-2016 there are seven years of pink salmon returns to the Fraser River as they appear in abundance only in odd years. Migration through the San Juan seine test fishery on the West coast of Vancouver Island indicated that in some years (2007, 2009) a single peak describes the passage of fish, with improvements in R^2 in those years of only 2.5% and 5.6%, respectively, for considering that there may be two pulses of migration. In the other years, 2003, 2005, 2011-2015, there were significant improvements in fit with R^2 increasing by as much as 19-42% by modelling this part of the migration as two pulses. A similar pattern appeared in the Blinkhorn seine test fishery, but some years differed in whether there was an improvement in the model fit by contemplating two peaks (Figure 49).

- The Blinkhorn seine test fishery has the added complication of greater abundances of local (non-Fraser) pink salmon in the catch. The worst fit to a two pulse model occurred in 2015 in the San Juan seine test fishery because there were three obvious peaks that year. This San Juan gillnet test fishery began relatively late in 2015 and first sets yielded catches there were the largest in first sets in the 21st century indicating that the pink salmon migration was already underway when the test fishery began, confirming the early arrivals seen in the seine test fisheries.

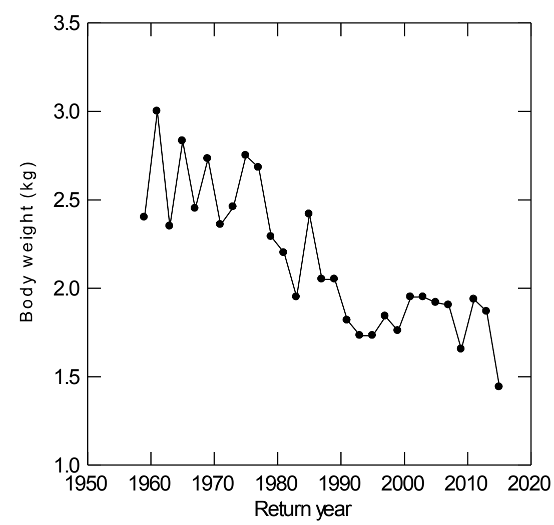


Figure 48: Mean body weight (kg) of pink salmon returning to the Fraser River.

Chinook salmon

- 2015 - the only extremum for large chinook salmon in Johnstone Strait was a late peak in the Blinkhorn test fishery. Small chinook salmon in the Blinkhorn test fishery had a skewness extremum (slow build to a peak) that was consistent with the late timing of the large chinook salmon. There were numerous extrema at the San Juan test fisheries; both small and large chinook salmon were the least abundant in the record in the gillnet test fisheries and most abundant in the record in the seine test fishery, suggesting a late migration timing, but the estimated peak dates were not extrema. The San Juan seine test fishery was the least compressed for small chinook salmon.
- 2016 - large chinook salmon had a compressed run in the Round Is. test fishery and the small chinook salmon had a skewed return with most arriving early. Large chinook salmon had an abundance extremum (low) and a compressed run in the Blinkhorn test fishery. There were no extrema for small chinook salmon at Blinkhorn. Small and large chinook salmon in the San Juan gillnet test fishery was the most compressed in the record. In the San Juan seine test fishery, small chinook salmon had the most skewed run (slow build to a peak) but no other extrema. Large chinook salmon on the other hand were the least abundant, a strong skewness anomaly (slow build to a peak), and a compressed peak.

Coho salmon

Coho salmon spawning migrations occur primarily later than these test fisheries operate.

- 2015 -the seasonal pattern of catch of coho salmon in the Round Is. was the least compressed in the record but there were no extrema at the Blinkhorn test fishery. At San Juan, the seasonal pattern of catch in the seine fishery was the least compressed and the peak date of the gillnet fishery was the latest in the record.
- In 2016, there were no extrema in the Round Is. test fishery but in the Blinkhorn test fishery, the abundance was lowest and compression was the highest. At the San Juan gillnet test fishery, abundance was lowest and in the San Juan seine fishery, compression was greatest.

Chum salmon

Chum salmon spawning migrations occur primarily later than these test fisheries operate.

- 2015 - there were no abundance/timing extrema in the Johnstone Strait test fisheries. In the Strait of Juan de Fuca test fisheries, there was an abundance extremum (low) in the gillnet fishery and a abundance extremum (high) in the seine test fishery.
- 2016 - the Blinkhorn Is. test fishery had the lowest abundance of chum salmon. Chum salmon caught in the Round Is. test fishery had the least compressed (most protracted) catch. These extrema also appeared at the San Juan gillnet and seine test fisheries.

Steelhead trout

- 2015 - the steelhead trout passing the Johnstone Strait test fisheries had low compression in both, but they also had an abundance extremum (high) at the Blinkhorn Is. test fishery. There were no extrema at either of the San Juan test fisheries.
- 2016 - the peak date of the steelhead passage past the Round Is. test fishery was latest in the record but there were no extrema of any kind in the Blinkhorn test fishery. Like other salmonids, the compression of the passage of steelhead trout catch in the San Juan gillnet test fishery was highest. Abundance in the San Juan seine fishery was the lowest.

U.S. Mainland

Baker Lake
The data from Baker Lake are reconstructed pre-fishery abundances of sockeye salmon. In 2015, their abundance was an extremum (high). There were no other extrema in 2015 or 2016.

Lake Washington
The data are sockeye salmon counts at Ballard Locks on the ship canal into Lake Washington. There were no extrema in either 2015 or 2016.

Columbia River

Juvenile salmon surveys - Annual trawl surveys conducted by NOAA along the Washington-Oregon coast typically find the highest abundance of coho salmon and chinook salmon near the Columbia River in May and June. CPUE varies from year to year with lowest abundances occurring during years of strong environmental anomalies such as the 1998 el Niño and the 2005 downwelling year (Figure 50). There were no extreme abundance anomalies in 2014 or 2015. The highest CPUE occurred in 2013. Growth rates of juvenile coho salmon measured in 2015 off the West coast of Washington and Oregon were second highest in the past decade (Brian Beckman, NOAA, pers. comm.); 2014 was highest.

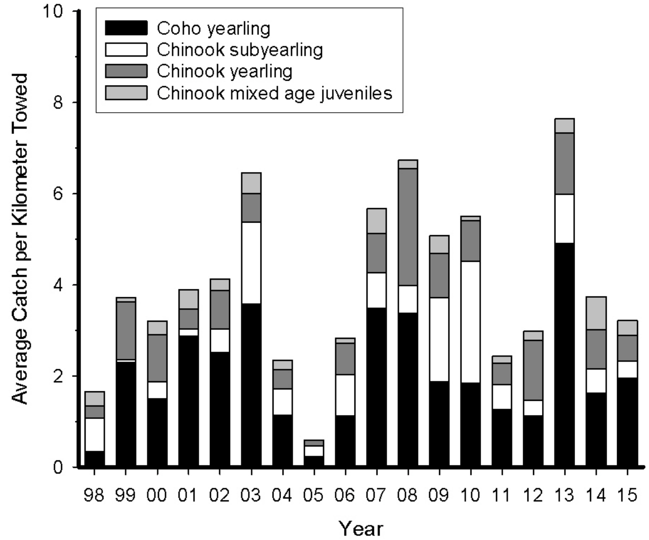


Figure 50: Annual variation in juvenile coho and chinook salmon CPUE during June trawl surveys, 1998-present. Source: https://www.nwfsc.noaa.gov/research/divisions/fe/estuarine/oeip/kb-juvenile-salmon-sampling.cfm

Chinook salmon - Chinook salmon return to spawn above Bonneville Dam at various ages. Larger individuals are counted as adults and smaller individuals as jacks, although both should be considered as adults according to their sexual maturity. Three run timing groups are recognized: Spring, Summer, and Fall. The Spring and Fall runs generally have prominent peaks of abundance and relatively compressed timing. The Summer group has a less compressed migration and when abundant, a peak is evident.

- 2015 - the total return of large chinook salmon was an extremum (Figure 51) as a result of Summer and Fall Run extrema added to a relatively high abundance of the Spring run. Spring and summer small chinook salmon were extremely skewed (peak during the first part of the run) and small Spring run chinook had a compression extremum (low).
- 2016 - No extrema.

Sockeye salmon - There are three populations of sockeye salmon in the run but they are so dominated by the abundance of the Osoyoos Lake population that the run was modelled as a single pulse.

- No extrema occurred in 2015 or 2016, although abundance was high in 2015.

Steelhead trout - The run of steelhead trout was modelled as a single pulse.

- 2015 - No extrema
- 2016 – Most protracted in the 21st century. Abundance was also low but not extreme.

Coho salmon - The fraction of coho salmon run ascending to spawn above Bonneville Dam is relatively small compared to the total run to the river (L. Weitkamp, NOAA, pers. comm.). Nevertheless there are at least two regular peaks annually for large coho salmon. The only peak date extremum (early) was found in the large coho early-run component.

- 2015 - The timing of large coho in the early run was extreme (early) and the run of late run coho was protracted.
- 2016 – There were no extrema in either run timing component in 2016. Although not an extremum of interest to this report, the 2014 ocean entry year produced remarkably few large coho salmon spawners in 2015, considering the sibling relationship that has persisted through the 21st century (Figure 8).

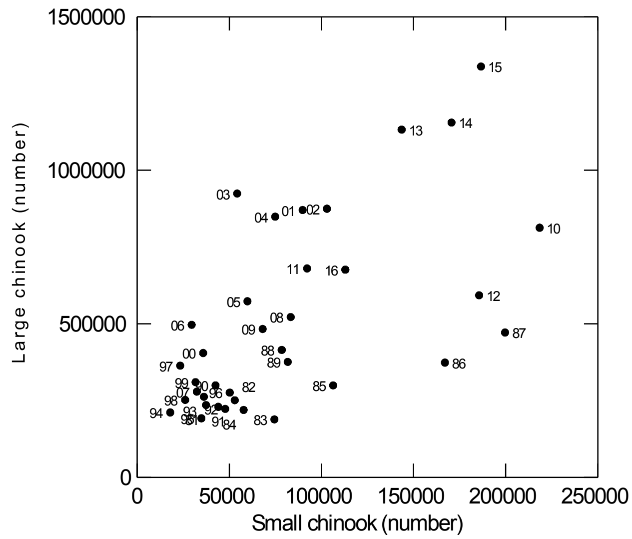


Figure 51: Annual numbers of large adult chinook salmon (year indicated on each plot point) returning to Bonneville Dam (Columbia River) versus the number of small adult salmon returning the previous year.

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Appendix 1. Oceanographic data and methods

1. Surface Air Temperature
   Monthly average surface air temperatures from the NOAA NCEP/NCAR Re-analysis at http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html
   Monthly anomalies were calculated by removing the monthly 1948-2016 long-term mean.

2. Sea Level Pressure
   Monthly average surface air temperatures from the NOAA NCEP/NCAR Re-analysis at http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html
   Monthly anomalies were calculated by removing the monthly 1948-2016 long-term mean.

3. Sea Surface Temperature
   3.1. Monthly average data are from ftp://ftp.emc.ncep.noaa.gov/cmb/sst/oimonth_v2/YEARLY_FILES/.
   3.2. Weekly average data are from ftp://ftp.emc.ncep.noaa.gov/cmb/sst/oisst_v2/YEARLY_FILES/.
   3.3. Daily average data are from ftp://eclipse.ncdc.noaa.gov/pub/OI-daily-v2/NetCDF/
   SST anomalies were calculated by removing the appropriate (monthly, weekly, or daily) 1981-2016 long-term mean.
   3.4. Kains Island lighthouse
   This lighthouse and many others, has been the site of daily measurements of SST and salinity since a program of sampling was started by the Fisheries Research Board of Canada in the early 20th century. Anomalies were computed as deviations from the long-term (1935-2016) daily averages. Data were downloaded from http://www.pac.dfo-mpo.gc.ca/science/oceans/data-donnees/lighthouses-phares/index-eng.html

4. Sea temperature and salinity depth at 5m depth.
   These data were collected and made freely available by the International Argo Program and the national programs that contribute to it (http://www.argo.ucsd.edu, http://argo.jcommops.org). The Argo Program is part of the Global Ocean Observing System. Because of their relatively sparse distribution (compared to satellite data), developing a climatology has some challenges. Two approaches were used to compute temperature climatology. The first computed average temperature and salinity in 2° latitude by 5° longitude blocks by month. Monthly average temperatures were computed from all observations made within a block/month. Long-term monthly averages for the block were calculated by summing across years (2003-2016) and dividing by the number of years with valid data. Anomalies were created by subtracting each monthly average from the long-term average in a block. A second approach was to use a satellite-based SST climatology made at a much finer spatial (¼° grid) and temporal (daily). When a float surfaced, its daily ¼° location was noted and the temperature it observed at 5 m was subtracted from the average for that time/location. Using a surface climatology to compute anomalies at 5 m will underestimate the true anomaly at 5 m because the average value at the surface is slightly warmer than the average value at 5 m.

5. Mixed Layer Depth (MLD)
   Mixed layer depth was determined according to the following definition: the expected standard deviation of repeated sampling of water properties (t, s, density) is equal to zero in a mixed layer. Each profile can be examined from surface to depth where this property should hold if the layer is truly mixed. A gradient in any property indicates that the layer is not fully mixed. In practical terms, the standard deviation can only approach zero in the mixed layer because of the precision of the

instrument and other factors associated with making observations. As a consequence, an arbitrary tolerance level is needed. In the present study, it was set at 99%, meaning that each measurement at depth is compared with the distribution of measurements taken at shallower depths. Assuming a normal distribution, if a deeper measurement had less than a 1% probability of coming from the distribution with the mean and s.d. of values measured above it, then the MLD was set as half the distance of the depth of that measurement from the one above. The rationale for the latter is that one doesn't know where in the last depth interval the change occurred so the midpoint was chosen.

6. Chlorophyll from satellite ocean colour

Chlorophyll concentration data products served by the NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group were used in this analysis. The initial download of data occurred in October 2015 with subsequent files downloaded intermittently since then. Analyses included data up to November 2016 (eg. http://oceandata.sci.gsfc.nasa.gov/MODIS-Aqua/Mapped/8Day/9km/chlor_a/2016. SeaWiFS sensor data (1997-2002) were downloaded from https://oceandata.sci.gsfc.nasa.gov/SeaWiFS/Mapped/8Day/9km/chlor_a/). Phenology was determined within each 1° x 1° cell within the salmosphere by fitting a McKinnell growth curve configured with two pulses (spring and fall) to a cumulative curve of 8-daily average chlorophyll concentrations. The average in an 8-day period in a cell was computed as the mean of all valid pixels within each time/space stratum. Missing data were replaced by the long-term mean of that day and grid point. Each time series was then smoothed by a 3-weekly running mean.

7. Plankton

7.1. Continuous Plankton Recorder (Pacific project)

Data for the current year are preliminary, based on processing 25% of the samples. Values are monthly means compared to the long-term monthly mean and minimum/maximum monthly values found in the time series to date since 2000. Numbers for 2016 will change as more samples are processed and quality-controlled. Four variables have been selected: total diatom abundance, mesozooplankton abundance, estimated mesozooplankton biomass (dry weight), and average copepod community size (based on Richardson et al., 2006 where the published length of the adult female represents all individuals of the species). These variables are thought to provide a useful summary of the plankton, but there are some caveats and limitations: 1) The CPR diatom numbers are biased towards the larger, chain forming varieties which may only be a small portion of the phytoplankton community, 2) the number of samples that the provisional data are based on is small, especially for smaller regions. Regions with the best sample density are: Oceanic NE Pacific, Alaskan Shelf, and S. Bering Sea. Three regions are sampled only by the east-west transect which runs only three times a year in spring, summer and fall (W. GoA, Aleutian Shelf and S Bering Sea). Monthly data for the Oceanic NE Pacific Region were provided by and courtesy to Dr. Sonia Batten, Director, CPR-Pacific). Reference: http://www.pices.int/projects/tcprsotnp/main.aspx.

7.2. Coastal sampling

a) British Columbia
   - figures were obtained from DFO's State of the Pacific Ocean report (Chandler et al. 2016).

b) Newport, Oregon
   - There is a relationship between water type, copepod species richness, and the PDO. Two indices were developed based on the affinities of copepods for different water types. The dominant copepod species occurring off Oregon at NH 05 were classed into two groups: those with cold–water and those with warm–water affinities. The cold–water (boreal or northern) group included the copepods Pseudocalanus mimus, Acartia longiremis, and Calanus

marshallae. The warm–water group included the subtropical or southern species *Mesocalanus tenuicornis, Paracalanus parvus, Ctenocalanus vanus, Clausocalanus pergens, Clausocalanus arcuicornis and Clausocalanus parapergens, Calocalanus styliremis*, and *Corycaeus anglicus*. Source: https://www.nwfsc.noaa.gov/research/divisions/fe/estuarine/oeip/eb-copepod-anomalies.cfm.

8. Appendix 2. Salmon data and methods

Modelling migration

Regular observations of salmon abundance at fixed locations are standard tools in a fishery manager's tool bag. The data collected are generally of two types: counts of individual fishes as might occur at the fish ladder, or numbers caught per unit of effort as might occur at a test fishery that is intended to gauge the abundance of passing fish. These types of regular sequential observations can be described by parametric models such as the 2 parameter Gaussian (normal model which assumes that a salmon migration can be described by a mean date and its standard deviation). More complex models such as that of Schnute and Sibert (1983) allow greater flexibility by using additional parameters to capture traits such as skewness (asymmetry) of the run and compression (similar to kurtosis) which permits curves with shapes ranging from a sharp peak in abundance through to no peak. The 4 parameter Schnute-Sibert curve can be expanded to entertain runs that exhibit multiple peaks (McKinnell, unpublished) that need to be “decomposed” from the composite data. The improvement in the fit as a result of entertaining multiple components (run timing groups) can be measured and compared with simpler curves by examining the improvement of the fit of the model to the data (R^2). Where long-term observations suggest a fixed number of peaks, such as the Spring, Summer, and Fall runs of chinook salmon to the Columbia River, the expected number of components in the run was fixed, in this case at 3 components. The model then estimates the peak date, skewness, compression, and abundance of each component from the data. This differs somewhat from traditional practice which uses fixed dates (May 31, August 31) to separate Spring/Summer and Summer/Fall. The McKinnell approach allows for year to year variability in the timing of passage of each component, i.e. a late Spring run might allocate too much abundance in the Summer run. The two approaches should not differ too much in this case because the Spring and Fall peaks of are clearly identifiable. In some years, however, the end of the Spring run and the beginning of the Summer run may be more difficult to detect. Small numbers of missing data appear in most time series.

As the model fitting procedure relies on cumulative abundances, missing observations (primarily in test fisheries) were estimated by linear interpolation using the abundance on the day before and the day following the gap. To make each year comparable, regardless of abundance, each cumulative count or CPUE time series was converted to per cent. This also allowed greater stability in model fitting. Numerical instabilities arose when runs with millions of fish were run with the same tuning as runs with hundreds of fish. The solution to this problem was to convert all to cumulative per cent, then back transform this to absolute abundances after a solution was found. Prior to fitting each series was smoothed using 3-day average smoother to reduce the influence of high frequency (day to day) variability. As the analyses were done in the fall of 2016, before all returns were in for 2016, a cutoff date in 2016 was set at October 21. In reality, this affected only the Bonneville Dam analyses as other observation sites had stopped operating by this date. To make cumulative counts at Bonneville in 2016 comparable with other years, long-term average counts were used in place of observations from October 22 to November 30, 2016. By the 2016 cutoff, the peaks of all species and all timing components within each species have been seen so the effect on the 2016 results should not be too great.[1]

Escapement monitoring

8.1. Test fisheries

a) Nass River

The Nisga’a Fisheries Program provides weekly in-season updates on program activities including

1 The coho salmon returns (large and small) at Bonneville were re-run with 2016 data to November 24.

in-season Nass salmon and steelhead run size forecasts and up-to-date harvest information. These updates are available in the above-linked document. This data, public announcements and Nisga'a fishery openings and closures can be accessed from the FTP site at: ftp://ftp.lgl.com/Nass%20Stock%20Assessment%20Updates/.

(See also: http://www.pac.dfo-mpo.gc.ca/fm-gp/northcoast-cotenord/nass-eng.html)

b) Tyee (Skeena River)

A gillnet test fishery has operated at Tyee since 1955 to determine the abundance of salmon and steelhead trout entering the lower Skeena River. The test fishery was developed to provide daily estimates of sockeye salmon escapements after removals by the commercial fishery. Tidal amplitudes exceeding 6 m are common in the region during spring tides, generating tidal currents of three to four knots. The net is allowed to drift within a channel measuring two to five kilometres long and 0.8 km wide. Until 2002, an undyed, fibrous nylon gillnet of 200 fathoms total length and 20 feet depth, made up of 10 equal length panels of mesh sizes 3.5 inches to 8 inches. Starting in 2002 a 6 strand "Alaska Twist" net has been used. Sets (1 hour) are made on both high and low water slack during daylight hours which usually means three sets per day. Daily escapement estimates are calculated for sockeye salmon while relative abundance and timing are calculated for the other species.

(Source: http://www.pac.dfo-mpo.gc.ca/fm-gp/northcoast-cotenord/skeenatyee-eng.html)

c) Fraser River

The Pacific Salmon Commission (PSC) manages in-season test fishing programs in Fraser River Panel waters and coordinates with Fisheries and Oceans Canada on other marine test fisheries off northern Vancouver Island. The primary pre-fishery sites for the Fraser River are Round Is. (gillnet) and Blinkhorn Is. (seine) in Johnstone St. and San Juan (gillnet and seine) at the entrance to the Strait of Juan de Fuca. At the beginning of the season, gillnet is used in the approach routes in the Strait of Juan de Fuca and Johnstone Strait before switching to seine nets when abundances tend to be at a peak. Test fishing with gillnets only occurs within the river. The starting and ending dates of each gear vary from year to year. Fishing effort is relatively constant but there are variations so the daily data were converted to CPUE.

As there are generally considered, for management purposes, to be four main run timing patterns for sockeye salmon in a season (Killick 1955), each year of data at Whonnock was fit to a composite run timing curve that entertained up to four timing curves as this fishery registers all timing groups. Because of the mid-season gear change in the San Juan and Johnstone Strait test fisheries, each generally sees only three groups. Likewise in most years, the migration of pink salmon is described better by a model that entertains two pulses of migration. Nevertheless, a single pulse model will capture much of the variation in migration timing/abundance. For simplicity of analysis and interpretation, only single pulse models were fit for the test fisheries on the approaches to the Fraser R.

(Source: Pacific Salmon Commission; http://www.psc.org/publications/fraser-panel-in-season-information/test-fishing-results/)

8.2. Fish Counts

a) Alaska

Counts and descriptions of the counting locations were obtained from the Fish Counts webpage on the ADF&G website (https://www.adfg.alaska.gov/sf/FishCounts/index.cfm?adfg=main.home). Locations were selected primarily for their duration and abundances. ADF&G retains intellectual property rights to data collected by or for ADF&G. Any dissemination of the data must credit ADF&G as the source, with a disclaimer that exonerates the department for errors or deficiencies in reproduction, subsequent analysis, or interpretation.

- Yukon River (Eagle)

This sonar project is located approximately 1,200 miles up the Yukon River, 6 miles below the village of Eagle and 16 miles below the U.S./Canada border.

- Anvik River

The Anvik River is a tributary of the Yukon R. located about 300 mi. from the estuary. This is sonar project that estimates the passing abundances of pink salmon (even year) and summer-run chum salmon.

- Russian River

The weir is located at the outlet of Lower Russian Lake, about 78 miles from the mouth of the Kenai River. It takes approximately 7 to 10 days for sockeye salmon to travel from the lower Kenai River to the weir depending on water levels. Travel times are estimates and can vary significantly from this depending on conditions. The escapement goal is 22,000 – 42,000 Early-Run sockeye salmon and 30,000 – 110,000 Late-Run sockeye salmon.

- Karluk River

Karluk weir is located on the west side of Kodiak Island. The weir is near the mouth of the river just upstream from the lagoon and near the village of Karluk. It produces what usually is the largest run of sockeye salmon on Kodiak Island.

- Copper R. (Miles L.)

The Sonar on the Copper River is located at the outlet of Miles Lake, about 70 miles from the Chitina dipnet fishery. It takes approximately 2 weeks for salmon to travel this distance, but this is highly variable depending on the water level. The water levels listed here are an indication of the general trends in the Copper River but may not be indicative of what is occurring at Chitina. The current escapement goal for Sockeye is 360,000 to 750,000.

b) British Columbia

- Nass River

The Nisga'a Lisims Government's Fisheries and Wildlife Department has conducted extensive fisheries research on the Nass River since 1992 in partnership with Fisheries and Oceans Canada

(DFO) and BC Ministry of Environment. The Nisga'a Fisheries Program celebrated 20 years of operation in 2011 and currently operates twenty annual stock assessment, catch monitoring, habitat, and management projects. The current objectives and priority activities of the Nisga'a Fisheries Program are to: monitor Nass salmon and steelhead escapement, monitor salmon and non-salmon harvests in Nisga'a fisheries, in accordance with the Nisga'a Final Agreement, determine factors limiting the production of Nass salmon and non-salmon species; and promote and support Nisga'a participation in the stewardship of Nass Area fisheries. (source: http://www.pac.dfo-mpo.gc.ca/fm-gp/northcoast-cotenord/nass-eng.html). Weekly fish wheel catches were obtained from ftp://ftp.lgl.com/Nass%20Stock%20Assessment%20Updates/).

- Docee Fence (Long Lake)

The Docee River is located in the Central Coast district of British Columbia in Management Area 10. The Docee River is less that one kilometre long and drains Long Lake into Wyclees Lagoon which drains into Smith Inlet. The Docee River Fence is located at the outlet of Long Lake. The Docee River counting fence has been in operation since 1972. A counting tower was in operation from 1962 to 1971. Daily sockeye escapement information recorded at the fence is used for the management of the commercial gillnet fishery in Smith Inlet. The counting fence generally operates from late June or early July to mid August. Sockeye are sampled from the fence for post orbital to hypural plate length and tip of nose to the fork of the tail length. Scales are taken from each fish for age determination. In 1998, the fence operation was expanded to include coho and chinook. (Source: http://www.pac.dfo-mpo.gc.ca/fm-gp/northcoast-cotenord/docee-eng.html)

c) Washington

- Baker River Trap (Skagit)

Adjusted daily Baker Trap counts, covering years 1992-2015 and 2016 (to September 28) are the sum of the raw daily trap counts plus fish harvested in Skagit Bay/River fisheries moved forward in time to when we think they would have reached the trap if they were not harvested. For example, if we assume an estimated travel time of X days from the mouth of the river to the trap, then the "adjusted" trap count for a given day would be the raw trap count on that day + fish harvested at the mouth X days earlier. We use these adjusted counts when looking at timing for in-season run size updates, etc., rather than the raw counts, because in recent years there have been substantial commercial/sport fisheries in the bay and river below the trap that could affect the raw timing curve. There are 4 different river catch areas, plus the bay, each with its own assumed travel time from the catch area to the trap. The estimated travel times we use are based on the results of a recent sockeye tagging study. I can provide you with more details if interested. Since these adjusted counts include trap + harvest, the sum of the daily adjusted counts for each year is the total terminal run size for that year.

(Source: Peter Kairis, Biologist, Snowonish Tribe, WA, email: PKairis@skagitcoop.org)

d) Lake Washington (Ballard Locks)

- Lake Washington sockeye salmon have been counted each year since 1972 as they enter freshwater at the Hiram M. Chittenden Locks. The Washington Department of Fish and Wildlife (WDFW) counted the sockeye from 1972 through 1992, and currently Muckleshoot Indian Tribe and WDFW staffs conduct the counts cooperatively. Although small numbers of sockeye enter the system in May and early June, the period from the second week of June through the end of July is the standard counting interval used to determine if there are sufficient sockeye to open fishing seasons. Sockeye counts begin on June 12th each year to provide consistent data from year to year. The sockeye are sample counted daily during set time periods as they pass through both the locks and the fishway, and the counts are converted into a daily total number of fish passing upstream.

(Source: Aaron Dufault, WDF; http://wdfw.wa.gov/fishing/counts/sockeye/)

e) Columbia River

The Fish Passage Center provides technical assistance and information to fish and wildlife agencies and tribes, in particular, and the public in general, on matters related to juvenile and adult salmon and steelhead passage through the mainstem hydrosystem in the Columbia River Basin.

(Source: Fish Passage Center; www.fpc.org)

8.3. Body size-at-age

a) Fraser River – average weights of pink salmon were provided by Michael Lapointe (Pacific Salmon Commission).

b) Nass River – Nisga'a Fisheries Program

c) Southeast Alaska – Leon Shaul, ADF&G

8.4. Marine survival

a) West Coast Vancouver Island and Strait of Georgia

- Survival estimates for hatchery and wild coho salmon are prepared and maintained by Steve Baillie, DFO – South Coast office

Part Two

Atmospheric and Oceanic Extrema in 2015 and 2016 and their Effect on North American Salmon; Analysis of extrema and recommendations

Table of Contents

1 Introduction

History of Blobs

The images in Figure 1 leave one with a memorable impression of the development and evolution of the 2014 "blob" of unusually warm water that appeared in the southern Gulf of Alaska in the winter of 2013/2014 and spread eastward in the following months and years. A good technical description of its properties at the ocean surface can be found in DiLorenzo and Mantua (2016). They called it a *heat wave* because of its persistence to 2015 (and has continued through 2016).

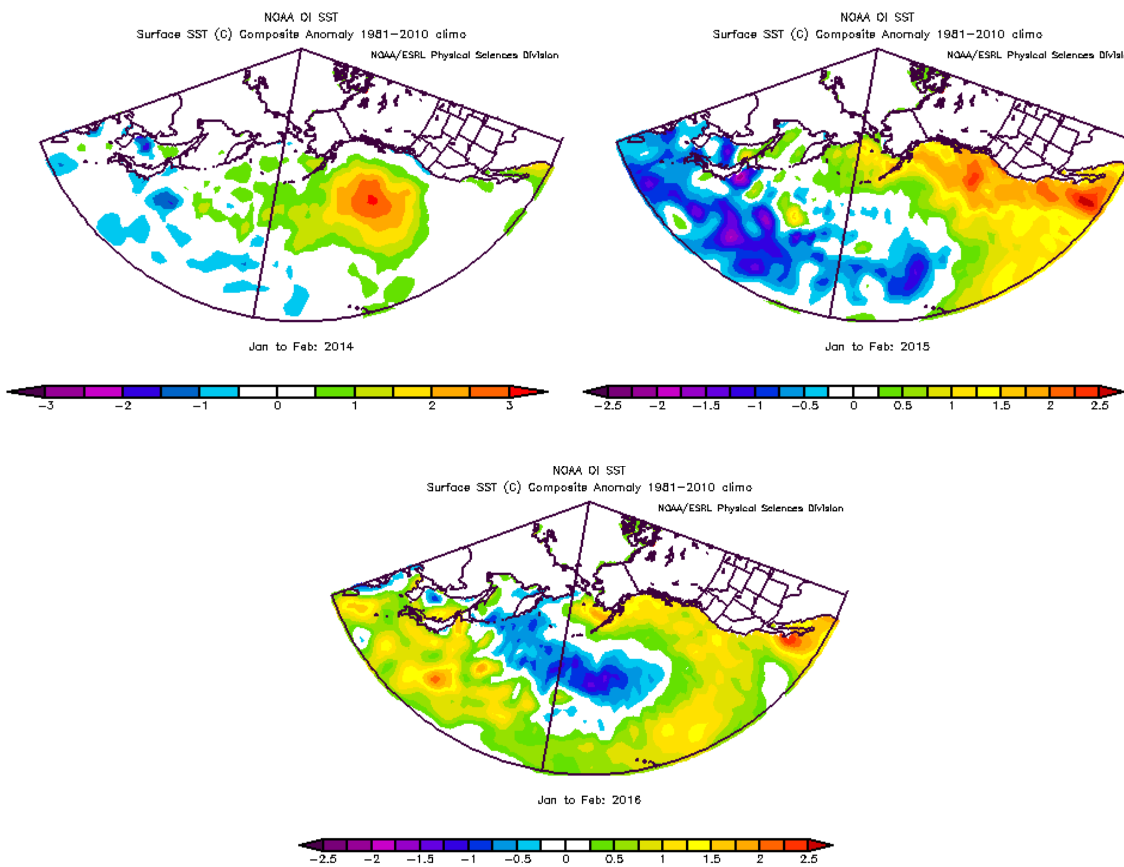

FIGURE 1: WINTER SEA SURFACE TEMPERATURE ANOMALIES IN 2014, 2015, AND 2016. THE COLOURS IN THE PANELS OF FIGURE 1 REPRESENT DEPARTURES FROM AVERAGE TEMPERATURE (°C) AND THE MAGNITUDE OF THE DIFFERENCE IS INDICATED BY THE INTENSITY OF THE COLOURS, WHICH CAN BE CHECKED AGAINST THE COLOUR BAR BENEATH EACH PANEL.

The warm blob of 2014-2016 was not entirely unique although some aspects of it certainly are. The most recent blob[1] prior to this one began 19 years ago in the spring of 1997 (Figure 2). It was of sufficient magnitude that, now as then, scientists dropped what they were doing to investigate. The PICES Science Board set aside a day-long symposium at their 1998 annual meeting in Fairbanks, Alaska for a discussion of and presentations on that event (Freeland et al. 1999).

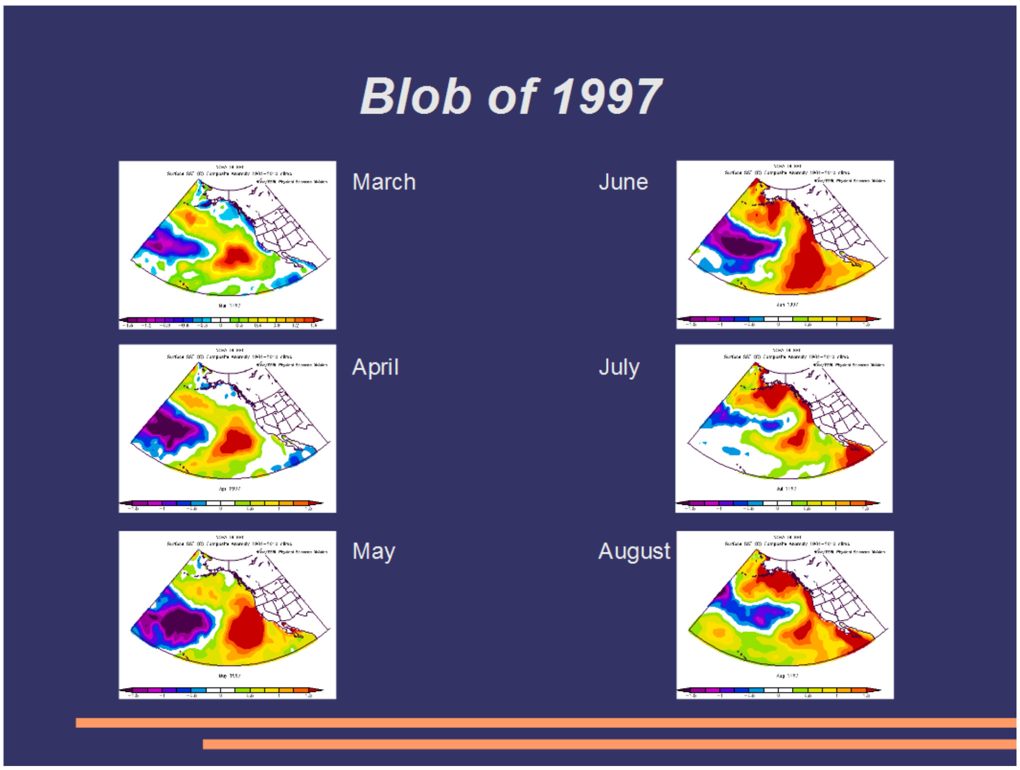

FIGURE 2: MONTHLY SEA SURFACE TEMPERATURE ANOMALIES DURING THE SPRING AND SUMMER OF 1997.

Salmon were involved then too. One of the more newsworthy events of 1997 was the straying of Fraser River sockeye salmon into rivers and streams along their normal oceanic migration route (McKinnell 2000). Toward the end of the run, maturation of some individuals had reached such an advanced stage while at sea that they abandoned their migration in favour of spawning. In several of these rivers, sockeye salmon had never been seen before. Spawning occurred but as far as has been determined, no new populations were established by the strayers. Most of the sockeye salmon made it to their destinations on the spawning grounds that year. The event was ephemeral and does not feature prominently in any of the long-term evolution of salmon fisheries or biology. As this is being written, the SST anomalies of 2016 have abated and even reversed sign, except in the Bering Sea (Figure 3).

1 It had triangular shape so it was called a triangle of anomalies.

Ten years ago, McKinnell and Crawford (2007) found statistical evidence in tree ring records and long-term temperature records that major el Niños tended to occur at slightly less than a bidecadal interval that coincided with the minima of one of the long-period tidal cycles (18.61 y). To test their idea, they published a forecast that a *major* el Niño should occur "around 2015" if their ideas about long-term variations in coastal temperatures had any substance. It was not a forecast for one of the garden variety el Niños that tend to occur at 4-7 y intervals and which has a high probability of occurring no matter what year is picked as the forecast, but a rip-roaring, equator-rattling, California-soaking, Okanagan vintage producing event, and that is what occurred during 2015/2016. What remains to be explained is why the recent event was so extreme (DiLorenzo and Mantua 2016), and perhaps why these events have been much more prominent since the mid-1970s. The next tidal cycle minimum will occur in 2034.

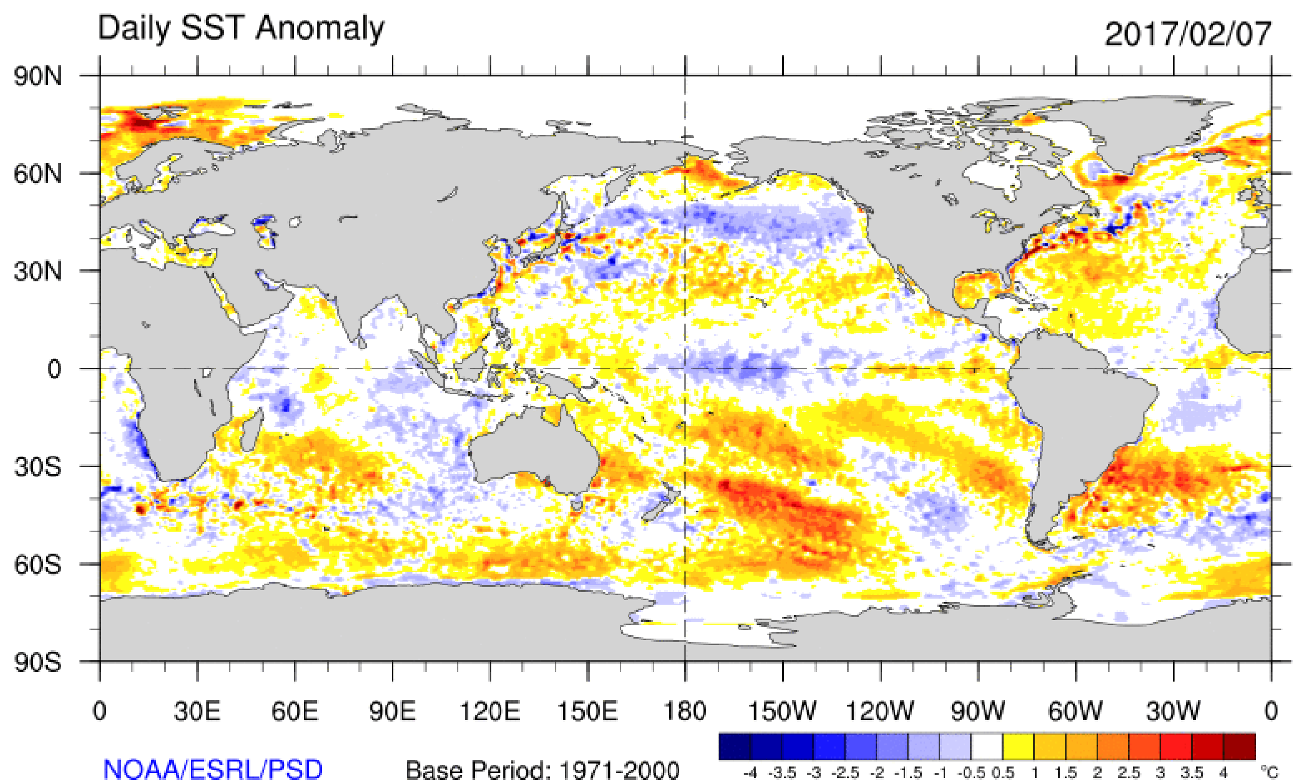

FIGURE 3: GLOBAL SEA SURFACE TEMPERATURE ANOMALIES ON FEBRUARY 7, 2017.

Extrema Project

The Extrema[2] Project (McKinnell 2017) examined some aspects of ocean-climate variability in the North Pacific Ocean during a recent period of environmental extremes that extended from the equatorial to the subarctic Pacific Ocean. Perhaps as a direct consequence of these extremes, some attributes of salmon

2 Unprecedented events.

biology (migration timing, abundance, mean size-at-age) in the northeastern Pacific Ocean were more extreme than anything observed, if not in history, at least in prior records. A healthy skeptic's view of this coincidence is that it was just that; the joint extremes in salmon biology and in the environment were unrelated. While this may be possible, it seems rather unlikely because the coincidence happens too frequently. Historical accounts of joint environmental and fisheries extrema on the North American coast indicate that extreme events in marine ecology and climate have been connected in some way. Scientists across disciplines have documented rather diligently how extreme environmental events are associated with extreme fisheries/biological events, beginning in North America with the CalCOFI report on the consequences of the 1957/58 el Niño (Sette and Isaacs 1960), the 1982-83 el Niño (Wooster and Fluharty 1985), the 1997/98 el Niño (Freeland et al. 1999). One career might normally expect to encounter only one or two of these so the topic may not always be foremost in thinking.

With the advent of programmable calculators, microcomputers, and spreadsheets, a correlation calculation became a button waiting to be pushed. In untrained hands, it has been pushed often. "*Seldom, if ever, has thought been given to possible mechanisms of these correlations*" (Laevetsu 1983) is a sentiment that persists to the present. Progress in understanding has been made during international programs such as GLOBEC (Barange et al. 2010). The Northeast Pacific is not without its own set of correlations, some of them well known (Beamish and Bouillon 1993; Mantua et al. 1997) but their value for prognostic purposes has yet to bear fruit. The average intensity of one of these purported explanators of salmon production variability, the intensity of the Aleutian Low, has risen and fallen for 25 years without much evidence that its variation is of much value in predicting salmon production (McKinnell 2016). Nevertheless, causal forces and biological responses to those forces should indeed be correlated if that signal is stronger than other causes of variation.

The first phase of the Extrema Project sought to find environmental and biological extremes in 2015 (and in 2016 if data were available). Biological extrema appeared in both years from the Columbia River to the Yukon River but there were many populations where extrema did not occur. Most were related to some aspect of variability in the nature of salmon spawning migrations. Extremes in population abundance or escapements, on the other hand, were both high and low but the full effect of the 2015 and 2016 extrema will not be resolved fully until 2018 for species with older age-at-maturity. Most of the survivors of these ocean entry years were still at sea when this report was written. Perhaps the most newsworthy event on the entire West coast was finding that the estimated abundance of sockeye salmon returning to the Fraser River in 2016 was the lowest ever recorded since the fishery began in the 19^{th} century. While preseason forecasts had called for low abundance, primarily because of the cyclic pattern of abundance seen in Fraser River sockeye salmon, are return this low return was unexpected. Fishwheels on the Nass River in northern British Columbia, on the other hand, recorded highest abundances of early-run sockeye salmon and late-run chinook salmon in 2016. At Bonneville Dam, 2015 was year of record high abundance (since 1980) of large chinook salmon. More often than not, measures of average body size of salmon were normal (within 2 standard deviations of the long-term average) in the populations examined (See Illustration 1 in the Appendix). The Trophic Gauntlet Hypothesis (McKinnell et al. 2014) offers one explanation for why Fraser River sockeye salmon might experience significantly higher mortality than other southern sockeye salmon populations, but its application to extreme ocean entry years has not yet been evaluated. Not all of the Fraser River sockeye salmon populations of the 2014 ocean entry year had poor (total) survival so the differences need to be examined more closely (S. Grant, DFO, pers. comm.). Where body size extrema were found in 2015, all were small, suggesting poor feeding and/or metabolic stress (warmer temperatures accelerate metabolic rates) for at least some of the populations. There were fewer records of body size available from 2016 returns but the one extremum was also small.

There was a broad and varied range of unusual behaviours by salmon populations in 2015 and 2016. Whether they were a direct result of environmental variation in the ocean in 2015 and 2016 cannot be known for certain, but given that salmon populations have changed their behaviours in the past in response to significant changes in the ocean (McKinnell et al. 1999), environmental extrema are the likely candidate for a cause. Whether the same responses would arise from a repeat of these years is not known; perhaps in some but not others.

Salmon are subarctic animals; they do not occur in the subtropics and they are not very abundant in the Arctic suggesting that their fate in the ocean is a function of the state of the subarctic ocean. When it was last examined, subtropical oceans of the world were expanding (Polovina et al. 2008). As the area of the ocean is not expanding (apart from sea level rise), some part of the World Ocean must be contracting as the World warms and the subarctic is a logical candidate. So salmon may be the canary in the mine, but the canaries that are most affected by such changes are probably those living at the limits of the range. Placing a canary on Kodiak Is. may not be the best indicator of a slowly changing system as it lies well within the interior of salmon oceanic habitat. Likewise, the coast of the U.S. mainland may be buffered somewhat from change because the entire coast is dominated by upwelling winds. On the other hand, if change occurs abruptly, in many places simultaneously, having canaries distributed from the Yukon to San Francisco can provide clues to the nature and scope of the change.

Continuing the avian metaphor, the Extrema Project was a canary hunt but what was found was a mixture of budgies, terns, parakeets and coots; that is, considerable diversity in what was recorded, but even moreso in what data were available. An original objective of the project was to identify anomalies, describe each, and provide advice on its implications and future monitoring. Almost everywhere on the coast there was some aspect of basic salmon biology in 2015 and 2016 that was more extreme than previously observed, at least in the last 40 years. In fact, so many large anomalies occurred that the focus of the investigation was restricted to the extrema among them, and there were so many of these that the discussion and recommendations had to be general rather than specific. As the environmental anomalies that gave rise to the project were found mostly in the ocean, no attempt was made to examine the effects of terrestrial expressions of this climate event (e.g. early spring in 2015) but it would be worth exploring.

Following a brief review (Section 2) of the approach used in this study, an attempt was made to evaluate common patterns where and if they were found. Section 3 attempts to evaluate the environmental and salmon extrema with a view in Section 4 to determine how the former affected the latter. Section 5 has a few key messages that emerged from the study and Section 6 provides some thoughts on where to go from here. Section 7 identifies some of the challenges to expect. Data sources and their treatment are described in Appendices 1 and 2 to the report of the first phase of this study (McKinnell 2017).

2 Data, methods, and definitions

a·nom·a·ly
əˈnäməlē/

noun: **anomaly**; plural noun: **anomalies**
-something that deviates from what is standard, normal, or expected.
"there are a number of anomalies in the present system"
Courtesy to Google for its definition

For the most part, the world view of "standard, normal, or expected" in the definition of anomaly above suggests some knowledge of what is average, calculated over some arbitrary period of time, and/or area of the globe. An anomaly is sometimes considered to be an oddity but that is not the correct meaning in the statistical sense that climate/salmon scientists might use the word. Daily experience with weather offers widespread familiarity with the concept of a statistical anomaly, for example when weathermen describe today's temperature and compare it to today's normal temperature. Years of watching weather reports reveals that today's temperature is almost never "normal" but varies above or below and typically by a small amount. This departure from normal is the anomaly; positive when greater than normal and negative when less than normal. Occasionally, some phenomenon occurs that is very different from normal and as a consequence, the anomalies are much larger than normal. Any anomaly that is unprecedented in an historical record, is an extremum (pl. extrema) which can be either positive or negative.

The early 1980s was used as a starting point for comparison, primarily as this was the beginning of the satellite-era of global sea surface temperature observations and historical data on salmon populations tend be rather sparse prior to this period, although there are some notable exceptions. A popular historical climate reconstruction database begins in 1948 (Kalnay et al. 1996) so searches for extrema in atmospheric temperature and pressure or winds can be span a longer period, however, evidence of climate regime shifts in these data (1976/77 for example) suggests that it makes more sense to restrict comparisons in this report to periods of variability that are relatively homogeneous. If an individual time series did not extend back to 1980, an extremum was assessed on the basis of whatever record was available. The online salmon test fishery data from the PSC, for example, begin in 2002 and relatively consistent satellite-derived estimates of chlorophyll concentration began in 1997.

Anomalies were classified as either: extrema, or normal (within ±2 standard deviations), or strong anomalies (>|2| standard deviations from the mean but not an extremum). Two standard deviations encompasses about 95% of observations in a Gaussian (bell) curve. Strong anomalies, as defined here, must be among the most extreme 2.5% negative or 2.5% positive to qualify. An extremum is simply the strongest positive or negative anomaly in the record examined, but could be less than 2 standard deviations and still be the most extreme in the time series.

Salmon model

Salmon runs in 2015 and 2016 were assessed by fitting daily abundances at fish weirs/ladders or catch-per-unit-effort (CPUE) in test fisheries to a timing/abundance model (Schnute and Sibert 1983) with parameters measuring: 1) abundance, 2) skewness[3], 3) compression[4], and 4) peak date. If only a single peak occurred in a run the Schnute-Sibert model was used. If a time series was a composite of multiple runs, the parameters for each component were estimated using a pulse model (McKinnell, unpublished) that decomposed the run into its component parts (eg. Spring, Summer, Fall chinook at Bonneville Dam) with

3 Parameter to indicate a long tail in either direction.
4 Parameter to indicate if the run compressed into a few days or protracted.

four parameters for each component. Each species and size-class (if distinguished) was fit to all years of data available (back to 1980) to allow the parameters estimated from 2015 and 2016 runs to be compared to historical results, to determine whether extrema had occurred in those years. Extrema, strong anomalies, and normal values were determined according to the criteria described above. A summary of the results using colour coded symbols for each run and year appears in Illustration 2 in the Appendix to this report.

Building climate indices

Salmon biology typically generates few data points per annum, like the annual number of salmon of each species passing through a fence. Environmental data on the other hand exist as time series at varying intervals (hourly, daily, weekly, etc.) and different geographic scales (1 km, 4 km, 9 km, 1º lat/long, etc.) and often everywhere on the globe. So the challenge is to reduce these data to a manageable level that will capture the main signals and allow the indices to be comparable with biological time series at geographic and temporal scales that are meaningful to salmon biology. A desirable property of an index is that it is resonant, which is to say that it represents variation in some property of nature across a broad geographic scale. One technique, among several that are regularly used for creating these indices, is principal component[5] (PC) analysis. At a geographic grid resolution of 1º latitude by 1º longitude there are over 4,500 time series in the region used to compute the Pacific Decadal Oscillation (PDO) index[6]. Typically, the value of a PC[7] is determined by the amount of covariation it reflects, often expressed as a percentage. The PDO index reflects about 20% of SST covariation. If it was 100%, it would mean that the PDO index reflected all of the covariation in SST in the North Pacific Ocean north of 20ºN latitude. At 20%, it means that much of the covariation in SST is not reflected in the PDO index. It is also possible from the analysis to determine where the PDO has greatest influence. As the PDO is a seesaw (cooler in the west while warmer in the east and vice versa), there are two "centres of action" both of which are in the subtropical North Pacific. The Extrema Project focused on developing new indices that reflect environmental variation only in that part of the North Pacific that is used by migrating salmonids – the *salmosphere*.

Scale

Whether about salmon biology or the environment, anomaly time series can be affected by local, regional, basin-scale or global processes. To understand why any particular time series varies as it does, whether

5 Different scientific disciplines give different names to this method.
6 Mantua et al. (1997) use at 5º grid to compute their PDO index.
7 Called a *mode* or and *EOF* in some scientific disciplines.

it be salmon or the environment, demands attention to scale. Because of the availability of global databases[8], it is possible to determine how resonant some ancient time series from a specific location may be. The spring temperature of the ocean at the Kains Island lighthouse on northwestern Vancouver Island, for example, is strongly influenced by atmospheric variability on a North Pacific basin scale (Figure 4). High sea level pressure in the western tropical Pacific is associated with low sea level pressure in the Gulf of Alaska via an atmospheric teleconnection, the PNA Pattern. Their combined effect when then PNA Pattern is positive is to warm the North American coastal atmosphere which in turn warms the coastal sea surface including Kains Island. When it is negative, the Kains Is. ocean is cool. Furthermore, the PNA Pattern has such a large footprint that it can affect coastal sea surface temperatures similarly from Scripps Pier in La Jolla California to Alaska. It is difficult to imagine, but sea level pressure in March in Darwin, Australia could be used as a crude indicator of the northern diversion of sockeye salmon to the Fraser River.

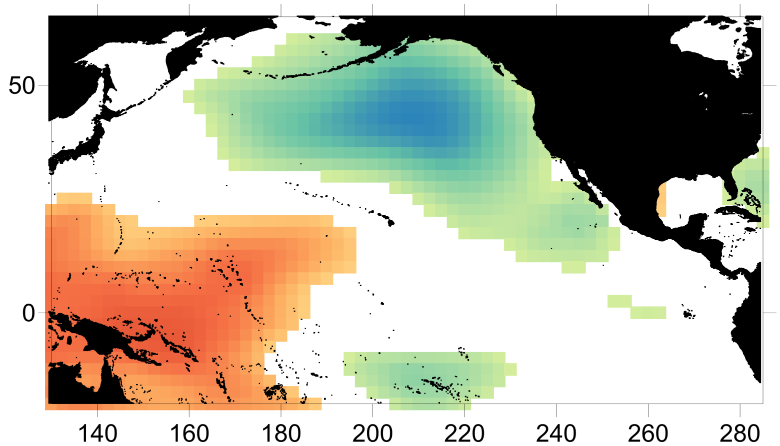

Figure 4: Correlation between Kains Island lighthouse sea surface temperature in March and atmospheric pressure (Pacific-North America Pattern).Only statistically significant correlations are coloured.

Salmon data

Based largely on on-line data, Phase 1 of the Extrema Project examined run timing and abundance of 69 species/timing/stock groups by fitting a model describing daily/weekly observations of abundance. Their geographic distribution ranged from the Bering Sea to the Columbia River although there were some notable gaps in southern British Columbia beyond the Fraser River watershed. Most time series came from the Fraser (30) and Columbia rivers (12). The Fraser River has multiple test fisheries catching all species but focused on sockeye salmon (and pink salmon in odd years). Because there are two major approaches to the river, an extremum in any year may also reflect migration route rather than abundance so caution is needed when interpreting these extrema. Observations from the Columbia River were taken from Bonneville Dam. More data were available from Alaska than were used but largely because of lack of time available to download them but representative locations and species with longer histories were selected.

8 Largely due to the efforts of NOAA/Climate

3 Review of extrema

Temperatures

Di Lorenzo and Mantua (2016) describe what occurred in surface layer of the Northeast Pacific Ocean in their analysis of sea surface temperature anomalies (SSTa) and sea level pressure anomalies (SLPa) from 2013 to 2015. Previous studies had identified a tropical role in Northeast Pacific SLPa during the winter of 2013-2014 (Whitney 2015; Bond et al. 2015). As there is also a relatively intimate connection between SSTa and surface air temperature anomalies (SATa), this connection and its evolution through 2016 was explored in the Extrema Project. As we know what causes summer to be warm and winter to be cold in most places in the ocean, the focus of study is the anomalies. In the first phase of this project, it appeared that most of the variation in SATa in the salmosphere was primarily a result of two dominant modes of variability. The first PC (28% of covariance) is a seesaw between the eastern and western salmosphere that is correlated with the Pacific Decadal Oscillation. When this index is positive, is is warm on the North American side and cool on the Asian side, and when negative the SATa are warm on the Asian side and cool on the North American side. The second PC (24%) causes salmosphere-wide warming when positive or cooling when negative across the region. Canonical correlation analysis (not shown here) indicated that both of these atmospheric patterns are needed to describe the dominant pattern of variation in SSTa within the salmosphere.

Air Temperature and Sea Level Pressure

By examining how SATa are related to SLPa throughout the Pacific Ocean (e.g. Figure 5), which are largely responsible for the wind anomalies in the North Pacific, it is apparent that the east/west seesaw mode in SATa has a global connection that is related to a large-scale atmospheric pattern in the Pacific that spans both hemispheres (Figure 5). Low SLPa in the eastern equatorial Pacific and the subarctic North Pacific are associated with higher SATa in the eastern salmosphere (Gulf of Alaska) and cooler temperatures in the western North Pacific (Asian side). SATa PC2 is associated with warming (when positive) or cooling (when negative) everywhere in the salmosphere, but is restricted to SLP variations within the northern hemisphere (Figure 6). When the Subtropical High Pressure system over Hawaii is weaker than average and the northern Gulf of Alaska has higher than average SLP, PC2 of SATa tends toward warming in the entire salmosphere. This pattern resembles the North Pacific Oscillation (Walker 1924), first described as an SLP seesaw between Alaska and Hawaii. Sometimes these two SATa modes are in phase and sometimes out of phase. A key point is that the connection of the salmosphere to the global climate system is needed to understand the nature of variability that is seen locally.

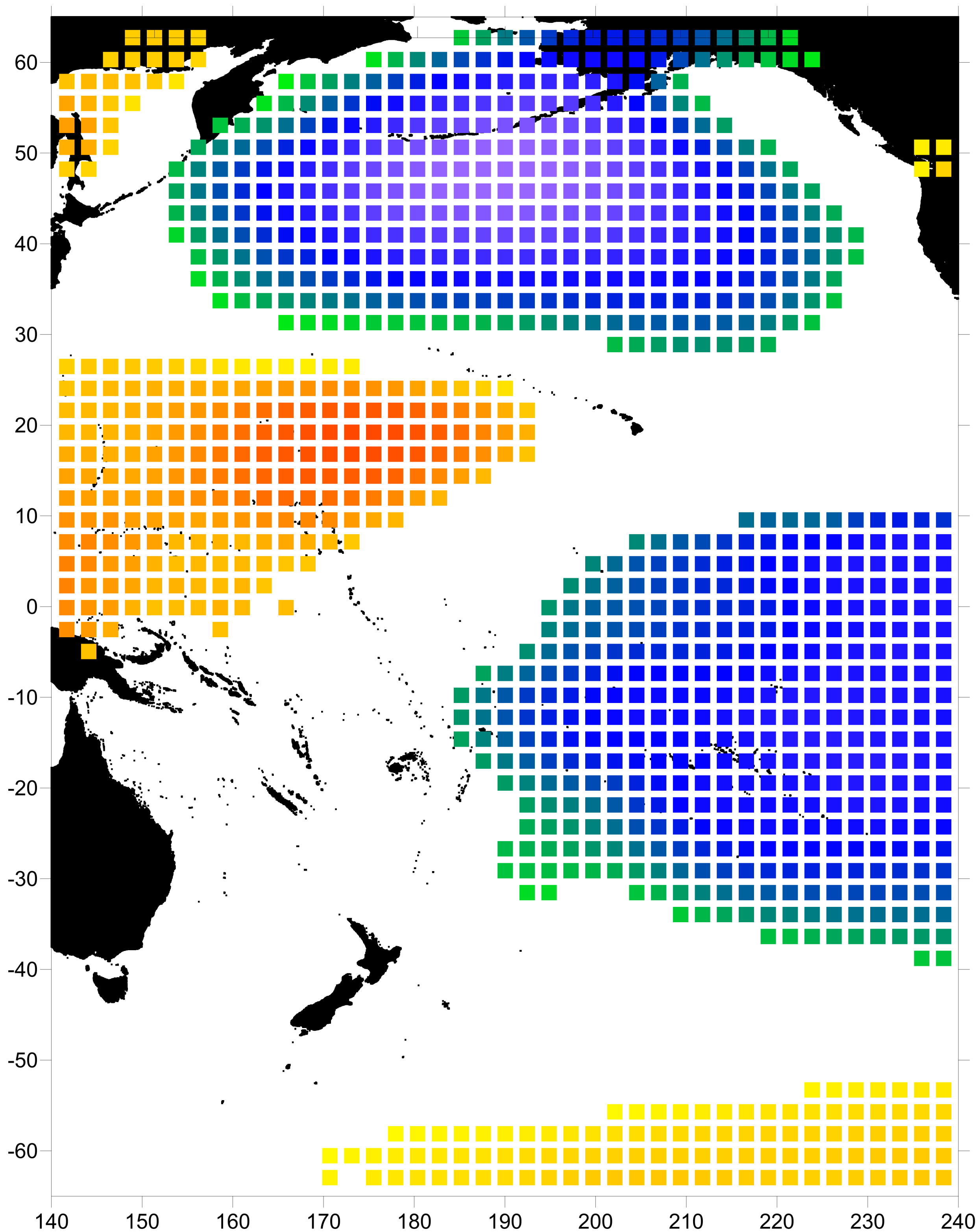

Figure 5: Statistically significant correlations between PC1 of surface air temperature in the salmosphere (the seesaw mode) and sea level atmospheric pressures in the Pacific Ocean. Stronger reds are higher positive correlations and stronger blues are stronger negative correlations. The range of correlations is -0.5 to +0.5.

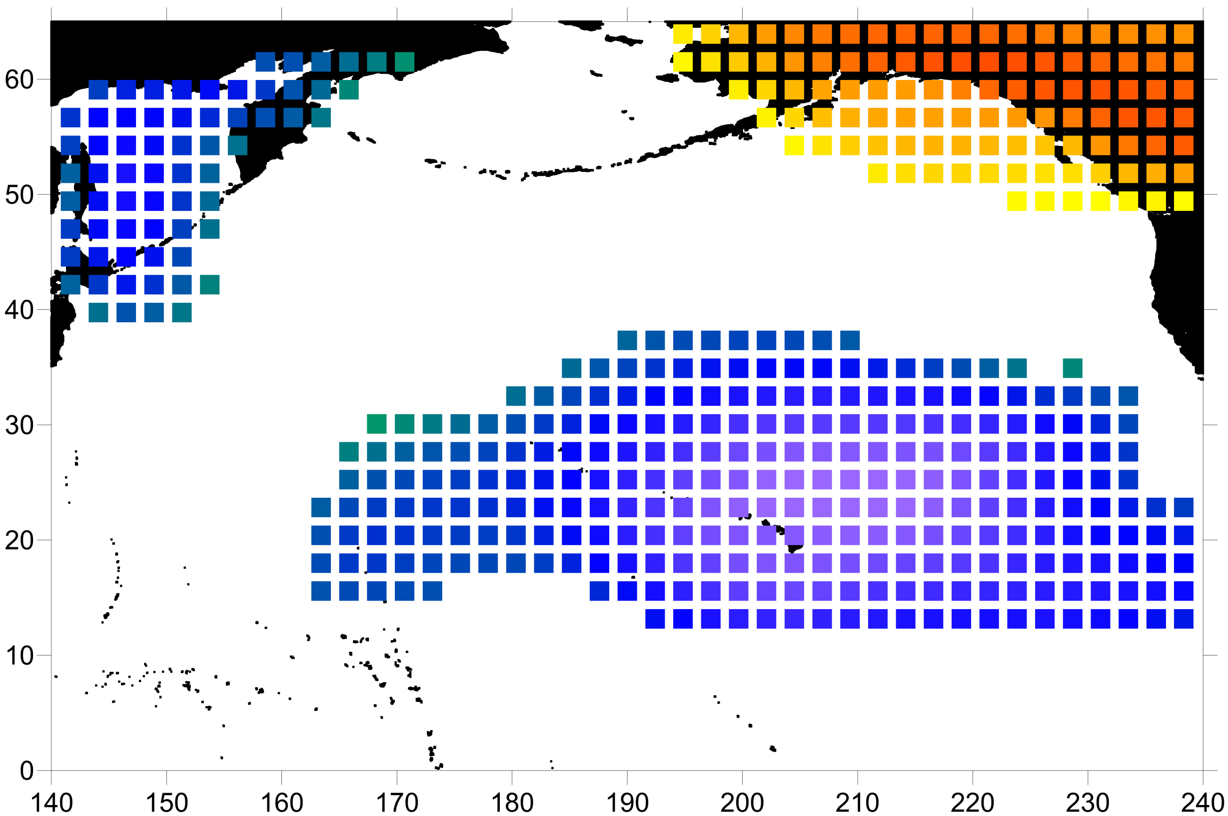

FIGURE 6: STATISTICALLY SIGNIFICANT CORRELATIONS BETWEEN PC2 OF SURFACE AIR TEMPERATURE IN THE SALMOSPHERE-WIDE MODE AND SEA LEVEL ATMOSPHERIC PRESSURES IN THE PACIFIC OCEAN NORTH OF THE EQUATOR. STRONGER REDS ARE HIGHER POSITIVE CORRELATIONS AND STRONGER BLUES ARE STRONGER NEGATIVE CORRELATIONS. THE RANGE OF CORRELATIONS IS -0.5 TO +0.5.

When the two major SATa modes are in phase and positive, as they have been since 2013, the Gulf of Alaska, the eastern Bering Sea, and the State of Alaska tend to be warmer than average. By selecting only those months when both modes are > +1 s.d. and plotting them by year, some regular patterns are evident (Figure 7). The first is that the joint positive anomalies are always associated with years of el Niños, and primarily the larger ones: 1957/58, 1986/87, 1991/92, 1997/98, 2002/03, and 2015/16. A second feature is that the number of months in each event is not directly related to the strength of the el Niño, as measured by contemporary ENSO indices. For example, the 1982/83 el Niño is not included in this collection or years, primarily because air temperatures were generally cooler in the salmosphere during that event. Thirdly, the occurrences of these jointly high values are not tightly restricted to the winter of the el Niño but span a period of one or two years before/after the el Niño, except for 1997 when all months occurred in that one year. Finally, the number of months in each event after 1997 has increased, but the time series is too short to know whether this is a trend. In conclusion, many el Niños energize both modes which leads to a warmer subarctic.

While this is not a new result, it is noteworthy that the warm temperatures appears to have arisen from existing modes of variation rather than some new pattern. The intensity recently was novel and is as yet unexplained (DiLorenzo and Mantua 2016). The oceanic temperature extrema seem to have arisen from an enhancement of two existing pre-dominant modes of SATa variability, one global and one hemispheric in scale. When the two modes are positive, as recently, they are associated with a generally warmer northeastern Pacific region.

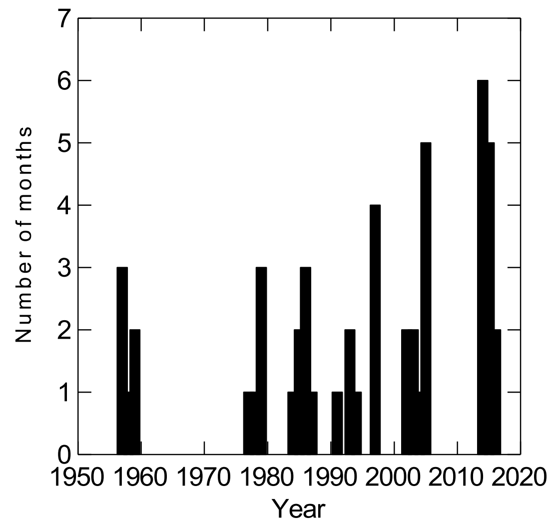

FIGURE 7: NUMBERS OF MONTHS, BY YEAR, WHEN THE DOMINANT AND SUBDOMINANT MODES OF SATA VARIATION JOINTLY EXCEED +1 STANDARD DEVIATION.

Sea Surface Temperatures

The most extreme sea surface temperate anomalies (SSTa) were located in the Bering Sea, far from the iconic image of the blob. This implicates the atmosphere as the cause rather than ocean circulation. The time series in Figure 8 is taken from a principal component analysis of weekly SSTa in the Bering Sea. It reflects SSTa throughout the Bering Sea in a single index, with positive values being generally warm and negative values being generally cool. It shows that the recent warm episode was similar in duration (to date) as a similar period that occurred in the first half of the decade of the 2000s, but the recent spikes of nearly 4.5 s.d. were far greater than found in a similar analysis of the entire salmosphere, or the continental shelf SSTa. The spikes in the Bering Sea occurred primarily in the warm season (none in winter) and were more frequent in 2014 and 2016 than 2015.

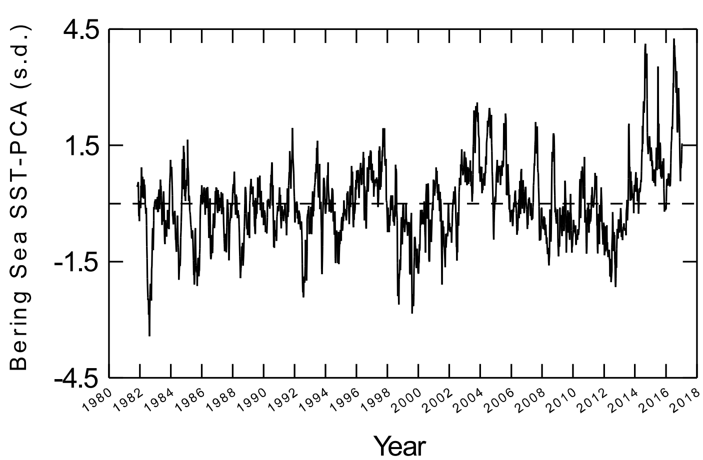

FIGURE 8: PC1 OF WEEKLY SEA SURFACE TEMPERATURE ANOMALIES IN THE BERING SEA FROM NOV 1981 TO JAN 2017.

Biological oceanography and juvenile salmon indicators

Since the late 1990s, oceanographers and salmon biologists from Alaska to California have been surveying the continental shelf and meeting annually to review the state of the coastal ocean and the state of the juvenile salmon found there. This coastwide interaction of researchers has led to a better understanding of the interaction between the environment and the salmon that live there by facilitating regional comparisons (Grimes et al. 2007). The region with the most anomalous phytoplankton and zooplankton anomalies was the U.S. West coast where salmon habitat indicators for the months of June in 2014, 2015, and 2016 were among the lowest in a 19 year record.

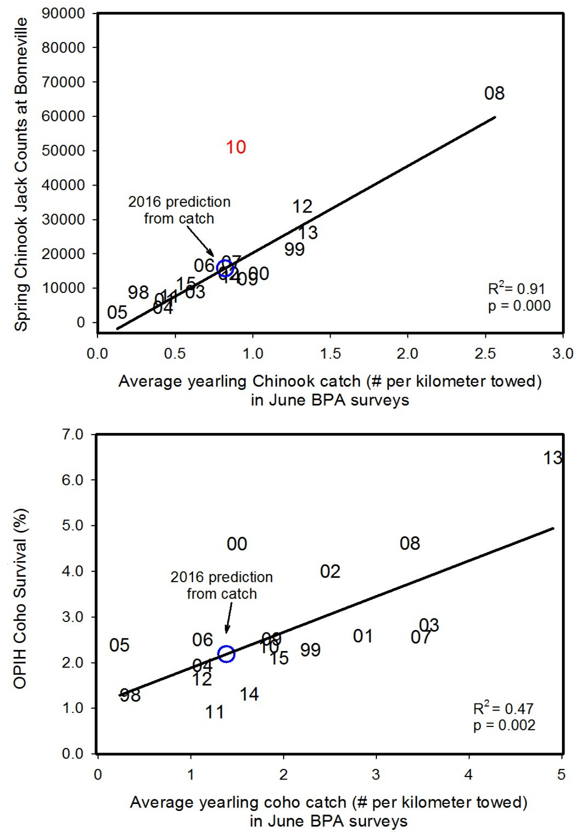

FIGURE 9: RELATIONSHIPS BETWEEN JUVENILE COHO SALMON ABUNDANCE IN JUNE IN BPA SURVEYS AND HATCHERY COHO SALMON SURVIVAL (BELOW) AND JUVENILE CHINOOK SALMON ABUNDANCE IN THE SAME SURVEYS AND SUBSEQUENT RETURNS OF AGE X.2 CHINOOK SALMON TO BONNEVILLE DAM. (NOAA/NWFSC)

"Locally, strong upwelling winds kept the Blob offshore of Oregon during summer 2014, but by mid-September, winds relaxed and the Blob flooded continental shelf waters with anomalously warm tropical/subtropical water. This resulted in a complete replacement of the "cold water, lipid-rich" food chain with a "warm-water, lipid poor" food chain. By winter (Jan-Mar) 2015, the SST pattern across the Pacific resembled the positive PDO pattern and this SST pattern continued through all of 2015 and 2016." (*https://www.nwfsc.noaa.gov/research/divisions/fe/estuarine/oeip/b-latest-updates.cfm*)

Typically, large-scale phenomena that give rise to warmer than average spring ocean temperatures along the North American coast are not favourable for the survival of juvenile salmon, as in 1998 and 2005, at least in the southern part of their range (up to Queen Charlotte Sound). From the results obtained to date in Bonneville Power Administration trawl surveys in these years, salmon survival on the U.S. West coast has been lower than average from the 2014 ocean entry year, as is typical in warmer years, but survival has not been as extreme (low) here as the habitat might suggest (Figure 9). In part, this may be due to a later arrival of the warm water along the Oregon coast. Upwelling winds could easily have kept a thin surface layer at bay until they abated.

Off the coast of British Columbia, in 2014 at least, coho salmon survival was as bad as the habitat indicators might have suggested (Figure 10). The 2014 smolt year in southern British Columbia had the lowest average survival in 30 years (S. Baillie, DFO unpublished). Surprisingly, juvenile coho salmon growth in 2014 was the highest ever recorded since the 1990s, perhaps because there was no competition among the few survivors. Growth in 2015 was also above average. In spite of two years of poor large-scale and local habitat indicators, growth was good (Chandler et al. 2015, 2016) but survival was not. A local wild population (Carnation Creek) on the West coast of Vancouver Island had the second lowest marine survival (0.3%) in the 2014 smolt year in a series that dates back to 2001 smolt year. Perhaps the coastal upwelling zone on the US. West coast provides a type of refuge that is not available to coho salmon in British Columbia.

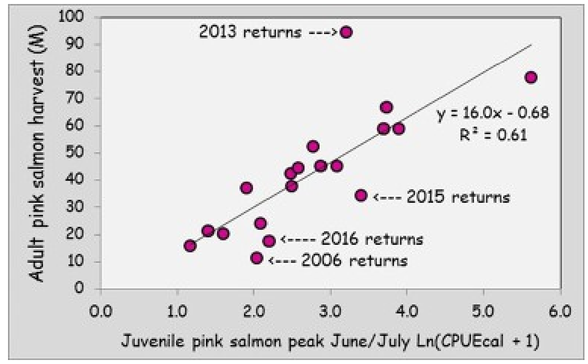

FIGURE 11: SE ALASKA PINK SALMON HARVESTS IN RELATION TO JUVENILE PINK SALMON CPUE DURING THE PRIOR YEAR. SOURCE: HTTP://WWW.AFSC.NOAA.GOV/ABL/EMA/EMA_PSF.HTM

A similar survey approach has been used in SE Alaska (Icy Strait survey) as the basis for developing a forecast of harvests of pink salmon in subsequent years. In 20 years of juvenile salmon surveys, the 2015 harvest arising from the 2014 ocean entry year, was the first significant overforecast of an odd year run in the history of the time series. The harvests in 2016 followed suit (Figure 11). Returns of pink salmon to the Fraser R. in 2015 were also much lower than expected (Fraser Panel News Release #10, 2015).

Adult Salmon

In the time available for this study, the more biological aspects of salmon extrema were given greater prominence than the commercial aspects (catch) although a better result might have been had if the two were integrated. Environmental extrema have a potential to affect body growth and size-at-maturity, age-at-maturity, migration timing, etc., so examining these properties across broad geographic scales can lead to a better understanding of how salmon currently use the ocean in the face of widespread environmental influences. The key results were summarized in Figures 1 and 2 of McKinnell (2017) and these figures are reproduced in the Appendix to this report. What is apparent by the prevalence of non-yellow colours in these figures is that salmon were either behaving very differently and/or were more or less abundant in 2015 and 2016 than in previous years[9] but the degree of abnormality varied from place to place. Across all 69 time series that were examined, there were 18 abundance extrema in 2015 (10 high) and 16 in 2016 (7 high). In both years, it appeared as though there was a mixture of highs and lows, but given the ocean ages

9 Where data are available to make a comparison.

of some of the migrants, there is a non-trivial probability that the cohort size was established before the oceanic extrema had a substantial influence on the salmosphere. The Columbia River had but one extrema in 48 parameters in 2016 despite being the southernmost river examined. Extrema there in 2015 tended to be the occurrence of highest abundances, but for species whose cohort size was likely established before the onset of the major oceanic anomalies in the salmosphere. Baker Lake and Lake Washington sockeye salmon showed similar results. Moving northward, the first strong anomaly in timing occurred with sockeye salmon at Long Lake (Docee River fence) with an early peak date in 2016 but not in 2015. On the other hand, the peak date of Skeena River sockeye at the Tyee test fishery was a late extremum, but fisheries seaward could have affected the shape of the run. The Nass River went from low abundance extrema in 2015 to high abundance extrema in 2016 for sockeye and chinook salmon, but a low extremum of coho salmon in 2016. Timing of the pink, chum, and chinook salmon populations in the Yukon River drainage was not extreme in 2015 but three different outcomes occurred in 2016: early (chinook), normal (summer chum), and late (fall chum and pink) extrema.

The Fraser River seems to be the oddity. Abundance/timing model results involved 4 parameters, 15 years of test fishery data, and 15 fishery-taxonomic-size combinations found numerous extrema in 2015 and 2016 at the test fisheries on the approaches to the Fraser River. If the extrema had all occurred in one year, there was a theoretical maximum of 60 that could be either minima or maxima. Therefore there should be 120 extremes (a minimum and a maximum for each combination of species and fishery) to be distributed somewhere among the 15 years (2002-2016) of data, or an average of 8 extrema per year based on chance, or 16 extrema in any two years. The results found that the total number of model parameter extrema in the two years of 2015 and 2016 was 52. Even a "chi-by-eye" suggests that something substantially non-random occurred in those two years. Despite the high number of extrema, there were more "normal" parameters (within ±2 s.d.) in those years than extrema or strong anomalies.

In 2016, all species in the Fraser River had at least one extremely protracted migration in one of the four test fisheries. Likewise these extrema appeared at least once in all test fisheries in 2016. The only other protracted run extrema was in the Nass River (late run chinook). All peak date extrema were early, with the exception of steelhead trout which were late extremum (Round Is. only). All run size extrema in 2016 were low: coho, steelhead, large chinook, small and large sockeye salmon, depending on the test fishery. There were no high abundance extrema in 2016. In 2015, all abundance extrema were low in the San Juan gillnet test fishery, but high in the San Juan seine test fishery. This suggests a timing event because the gillnet fishery precedes the seine test fishery, but none of the peak dates were extrema so more likely, it reflects abundance in Juan de Fuca. Some of that low abundance would be due to extreme northern diversions, at least for sockeye and pink salmon, in 2015. Rather than the protracted runs that had occurred during 2016, most of the migration extrema in 2015 had highly compressed runs.

In 2015, the returns of pink salmon in Prince William Sound and further west were good but they weakened toward the southern end of the range of the species (A. Wertheimer, pers. comm.). Low returns in 2016 in northern SEAK (Inside) were due in part to very low escapement in 2014, but the outside populations had better escapement in 2014 yet it resulted in low returns in 2016. In 2016, however, runs were poor from northern SEAK along the Gulf of Alaska to Prince William Sound and Kodiak. The spatial scale of these salmon anomalies almost exactly matched the SSTa in the winter before they went to sea (Figure 1). The full effects of environmental extrema in 2015 and 2016 on sockeye, chinook, and chum salmon and steelhead trout abundances will not be known with any certainty until the 2017 and 2018 returns.

4 Consequences

The occurrence of extrema in the salmosphere is not novel. For much of the 20th century, they came and went with little thought to their persistence. The last 50 years of experience suggests that that view needs to change but not necessarily because of blobs. In 1978, when the northern diversion of sockeye salmon returning to the Fraser River reached about 80%, it was considered as a simple anomaly as had occurred in 1926, 1936 or 1958 but then largely forgotten. It occurred to none in the late 1970s that the northern diversion would not return to average historical levels. The coincidence of the change in migration with a major shift in the climate system in 1977 eventually drew attention to the idea that large-scale physical forces were affecting at least some aspects of salmon biology (Hare and Francis 1995; McKinnell et al. 1999).

Human responses to such findings will range from indifference to high anxiety depending on whether the occurrence of extrema are perceived as beneficial or detrimental to interests, immediate or long-term, in some aspect of the resource. At issue is a need to understand how, and how quickly the salmosphere is changing. Most climate projections of the IPCC[10] show relatively smooth transitions from now into the future and all involve warming. Because of inherent variability, some of it random, in the observations of salmon made each year, the general consequences may not be understood without having a relatively broad view of what is occurring on the coast.

10 United Nations Intergovernmental Panel on Climate Change

A new scientific imperative has emerged; to determine whether any strong anomaly is simply an extreme of random variation about a long-term average, or whether the anomalies of the kind observed recently in the Northeast Pacific, are the beginning of some new state of nature from which future anomalies should be calculated. The actions taken by managers now, in response, will have greater or lesser influence on the resource depending on which type of anomaly is occurring. There are recent examples that we are not yet very good at distinguishing one from the other, at least in a timely fashion.

Within living memory of some[11] there was an abrupt and persistent reduction in abundance of coho salmon in the Strait of Georgia (and Puget Sound). Abundances plummeted in the early 1990s, have never recovered, nor has a cause has been identified. The collapse was first reported (in Canada) by a scientist working in the Cowichan River (Holtby 1993) who attributed the cause of rapidly declining abundance, accurately as it turned out, to declining smolt survival rather than fishing. Response to this news was "*we need more details re specific, testable hypotheses*" (Humphreys et al. 1994) which was followed shortly thereafter by a request to scientists to reconsider the data to determine whether an increase in coho salmon exploitation was warranted, despite of growing evidence that the change in abundance was widespread and trending downward (Kadowaki et al. 1994). The response time to take management measures that were commensurate with the magnitude of the collapse of coho populations was about 5 years (almost 2 coho generations), and a change of Minister. Lack of experience with a simultaneous collapse of many populations was likely one of the reasons for the slow response. One hopes that in the 21st century, we have become more aware of the idea that fundamental changes may persist. The implications for future salmon production, management, forecasting and other needs depend on two things: 1) understanding the difference between an anomaly and a regime change, and 2) understanding the consequences for salmon of whatever the novel state of nature might be. A warmer ocean, especially in the south, has never been good for salmon survival. Global climate models are not predicting ocean cooling.

It was not possible to understand the full effects of environmental extrema on salmon species that spend more than one year in the ocean because these cohorts have yet to return to spawn, but coho salmon, pink salmon, and small sockeye salmon spend only one year at sea before maturing. In the Fraser River test fisheries, where coho salmon are caught incidentally, there were no extrema in coho salmon catches in 2015 (2014 ocean entry year) even though it was the year of worst average survival generally in southern British Columbia. On the other hand, two of four of these test fisheries had low abundance extrema for coho salmon in 2016. Fraser River pink salmon abundance in 2015 was much lower than expected (but not an extremum) but their mean body weight was the smallest in a record that dates back to 1959. Puget Sound

11 The author had just been appointed Chairman of the DFO PSARC Salmon Subcommittee during this era.

coho salmon were also small and in low abundance in 2015 (L. Weitkamp, NOAA/pers. comm). Because pink salmon and coho salmon mature after only one year at sea, their migrations do not extend far offshore. Sharing an ocean environment with insufficient prey could explain coincident anomalies in different species. Historical high seas tagging suggests that Fraser River pink salmon and Southeast Alaska pink salmon shared the same ocean habitat (50 years ago) but there were no body size extrema in SEAK pink salmon. Whether they share a common environment in the 21st century is unknown but the lack of synchrony in mean weight in 2015 suggests that they were not in the same oceanic environment. For longer lived species such as chum, sockeye, and chinook salmon and steelhead trout, the full effects of environmental extrema in 2015 and 2016 on abundances are not yet evident because oceanic anomalies tend to be more important for juvenile salmon than for maturing salmon. The low abundance extremum in small sockeye salmon catches in Fraser River test fisheries in 2016 may be telling. Generally, in the south there is no reason to expect that warm anomalies in 2015 and 2016 will translate into positive outcomes for returns. At one time, there was an idea that the productivity of salmon populations had a north-south seesaw; low (high) in the North while high (low) in the South (Mantua et al. 1997; Hare and Francis 1995) but this idea does not appear to hold in the 21st century.

The current study has focused on covariation of salmon extrema in extreme years. Understanding the scales of variability will help to determine the scope and nature of monitoring for change. In the populations examined to date, biological extrema in salmon populations were widespread, but the responses were not consistent between the years examined nor among populations. Some consistencies among species and test fisheries were found within the Fraser River. In part, the differences in salmon responses between 2015 and 2016 may have arisen because the nature of the environmental conditions differed between years, with 2015 following the year of the blob then leading into an el Niño and 2016 feeling the brunt of the el Niño before tailing away in the autumn from its major effects. SST extrema were more abundant in the Gulf of Alaska in 2016 than the preceding years.

5 Key messages

Although it is always difficult to generalize about salmon, a few key messages seemed to emerge from this study:

- The ocean-climate events of 2014-2016, although extreme in the instrumental records and widespread in the salmosphere, are likely to be ephemeral if this event is similar to what occurred in 1997/98. It came and went without leaving permanent effects either positive or negative on most salmon populations. The next one should occur around 2034.

- Where widespread changes (declines) in survival have occurred, as in salmon associated with the Salish Sea, they began in the early 1990s and have persisted to the present. These are fundamental changes that are not well understood but have lasting consequences.
- Extreme responses by salmon to ocean-climate extrema in 2015 and 2016 were coastwide and diverse but varied among species and region. Some runs were the most abundant during the years studied and some were the least abundant. More often than not, the salmon anomalies were in behaviour as they navigated their way around the novel environment.
- Evidence of late-life mortality in salmon in the sea is relatively rare. Most of what occurred in the last few years would have affected the juvenile salmon. Those with longer oceanic lives have yet to "show their hand." We have already seen the effects on pink salmon and coho salmon as they live only one year at sea. Southeast Alaska pink salmon have been much below forecast for two years, as was the case for the 2015 return to the Fraser River. Furthermore, the region-wide survival of coho salmon in southern British Columbia was the lowest on record for the 2014 ocean entry year.
- On a more practical note, assembling a coast-wide perspective on ocean-climate environmental variation and even developing new indices tailored to the salmosphere was easy. Doing the same for salmon biology was not. The main difference is that agencies responsible for the former have committed to collecting, organizing and distributing standard data products online to a diverse set of clients in different regions/countries. It requires an interagency commitment that has yet to occur in salmon biology, and may not be necessary if regional comparisons are not needed.

6 Moving forward

If salmon populations responded to extreme environmental conditions independently, and did so in unpredictable ways, there would be little value added with a coast-wide monitoring program. Marine survival of coho salmon has shown that in some cases, populations in entire regions can vary coherently but the only way this was known was to monitor coho salmon populations at a scale that could detect the pattern. The recommendations are offered with the assumption that the Commission is not getting the broad-scale perspective that it may wish to have and is interested in developing a coast-wide view of the salmon resource as it emerges each year.

1. The Commission needs a ***Salmoscope*** that would allow any Commissioner, or anyone with an

interest in salmon to understand, at the press of a button, how salmon returns are developing coast-wide, in-season. For example, imagine the figures at the end of this report as a computer screen that is updated daily, without requiring human intervention, that will identify strong anomalies (positive or negative) or extremes and issue alerts on these on a day to day basis.

2. The Salmoscope will require a Salmon Data Network (SDN) to facilitate the collection, organization, and dissemination of data from observing locations across international boundaries with the intent of increased understanding of the state of the resource. An expert group should be formed to design a network system that will provide real-time access to salmon data coast-wide, in-season. In the 21st century, it is technically feasible for a datum to be entered (once) into a computer on the SDN and served immediately to a global community. Impediments to developing such a system are not technical.

3. The Salmoscope will require at least two national salmon data servers offering identical data in identical formats that do not require human intervention to obtain (as is currently the case) and non-proprietary software must be the primary format. There are precedents in the climate and oceanography communities. Project Argo, for example, serves identical data from redundant servers in France and the United States. An expert group, perhaps working in concert with the SDN expert group, should be formed to advise on what data to serve in what format from what locations. There will be a need for a Salmon Data Archive (SDA) to serve as a repository for historical data, presumably served by the same servers.

4. The Salmoscope will require an expert group to design the Salmoscope around information needs of major clients by determining what needs to be seen to understand coast-wide, or regional phenomena.

5. The Commission should invest in the development of technologies to speed up the timeliness of obtaining salmon data. For example, in the 21st century it has become possible because of innovation to know today's depth of the ocean mixed layer, its heat content and salinity anywhere in the World Ocean without sending a ship to sea. Salmon biology needs equivalent scales of innovation to address the basic problem of getting an understanding of what is happening to salmon populations. We need to know the age of a fish when we catch it, not next November. It would be useful to know how it has been growing when it is caught, not waiting 5 years to apply for a grant (several times), to eventually learn how something grew 10 years ago. These kinds of advances will require automation that will only come from innovative thinking and a commitment

to improving the life of a salmon biologist. An expert group might be formed to identify areas where technical advancements are required and to set priorities on which challenge to address first.

6. After the expert groups have done their work and reported to the Commission, say in 3 years, implement the vision with a small pilot project of about half a dozen rivers (with willing participation) to understand feasibility and issues associated with delivery of the system. More rivers and sites can be brought on-line once the bugs have been worked out.

7. Environmental indices should be developed for the Salmoscope that reflect environmental variation broadly across the salmosphere, and regionally as appropriate, with a view to determining their predictive value for various aspects of salmon biology.

8. As a general rule, a census of salmon abundance should be taken as late in (a salmon's) life as is practical but before substantial fishery removals occur. If taken at or near the time when the juveniles enter the sea, some division of mortality between freshwater and marine sources is possible. There is little doubt that prior knowledge of spawner abundance has value: preparing for fisheries, as an indicator of management success, and as a basis for predicting future returns. Concerning the latter, the worst (easiest) time in the life history of salmon is a census made on the spawning grounds, while the best (most difficult) time for census of spawner abundance is made just prior to a fishery.

7 Challenges

Where they exist, a variety of data systems have been created by agencies to report in-season abundance of adult salmon. Presumably, they are meeting the needs of local users of the information but if they are not, now would be a good time to expand the dialogue to include those who wish to have a broader perspective on the resource. It is not currently possible to compare, even retrospectively, annual salmon runs along the North American coastline without significant human “intervention” in the process. It is not currently possible to compare runs in real-time within a season. Both are technically possible but there are impediments to progress that will take vision, leadership and time to overcome.

1. Currently, no person, entity, or organization has a responsibility, authority, and resources to obtain and serve salmon data coast-wide.

2. Data serving culture is not well established. Where exceptions, all use different approaches. There is no vision for how to organize salmon data to serve a coast-wide perspective.

3. No coast-wide data standards.

4. Limited access to parameters other than abundance or relative abundance. It is not possible, for example, to determine whether a brood year is "missing" from a run of multiple age-classes. This would be evident if salmon could be aged quickly. The extent of any anomaly could be understood if multiple rivers were examined.

5. Data access

    1. Finding the data; there is no online catalogue of coast-wide salmon data.

    2. When online sites are found, the effort required to get the data varies from site to site.

    3. Without exception, all online salmon data required human intervention to obtain, sometimes involving multiple steps. It is impossible, for example, to analyze salmon data reported in a pdf file, or displayed on a website without reformatting.

    4. If data were available to download, sometimes it was stored in a proprietary software format (eg. Excel) that is not readable by other kinds of software.

6. Weak history of innovation in salmon biology

    While there have been some notable exceptions, such as the development of genetic stock identification techniques, obtaining the basic biological information about salmon has not changed much since Gilbert started his program in 1914. Salmon biologists need counts, length, weight, age, and sex to begin to make sense of what they are observing. This minimal set of measurements is rarely met in most sampling programs.

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10 About the Author

Dr. Stewart (Skip) M. McKinnell [B.Sc. (Zoology, with distinction) UVIC, Ph.D. Sveriges Lantbruksuniversitet] began his career in marine science in 1979 as an oceanographic technician (UBC) serving on a coastal tanker in British Columbia before taking over as head of scientific computing at the Pacific Biological Station for 10 years. Beginning in 1989, he lead Canada's high seas research into the effect of large-scale driftnet fishing by Asian fisheries in the North Pacific. After the United Nations moratorium on this type of fishing was achieved, he served as Chairman of the DFO PSARC Salmon Subcommittee for two years and started the Atlantic Salmon Watch project to understand the fate of Atlantic salmon escapees from salmon farms. His Ph.D. described the interplay between Atlantic salmon biology and fisheries in the Baltic Sea. He was the first lead author of DFO's Wild Salmon Policy before leaving DFO in 1999 to take a position as Deputy Executive Secretary of the North Pacific Marine Science Organization (PICES) located at the Institute of Ocean Sciences, Sidney, BC where he worked for 15 years. Some of that time was spent as Editor-in-Chief of two international reports on the state of marine ecosystems of the North Pacific Ocean. He contributed to the 5th Assessment Report of the United Nations Intergovernmental Panel on Climate Change. While at PICES, Dr. McKinnell was lead author of an invited report to the Cohen Commission on the relationship between marine ecology and Fraser River sockeye salmon and the cause(s) of their decline, their extremely low abundance in 2009, and extremely high abundance in 2010. This work led to the Trophic Gauntlet Hypothesis for Fraser River sockeye salmon marine survival. He is an author or co-author of 50 primary publications and editor of a dozen special issues in the primary literature. He has written 75 technical reports on various fisheries and oceanographic subjects. He left PICES in 2014 to work as an consulting salmon oceanographer and in 2017 became master and commander of a personal research vessel, *R/V Gauntlet*.

11 Appendix

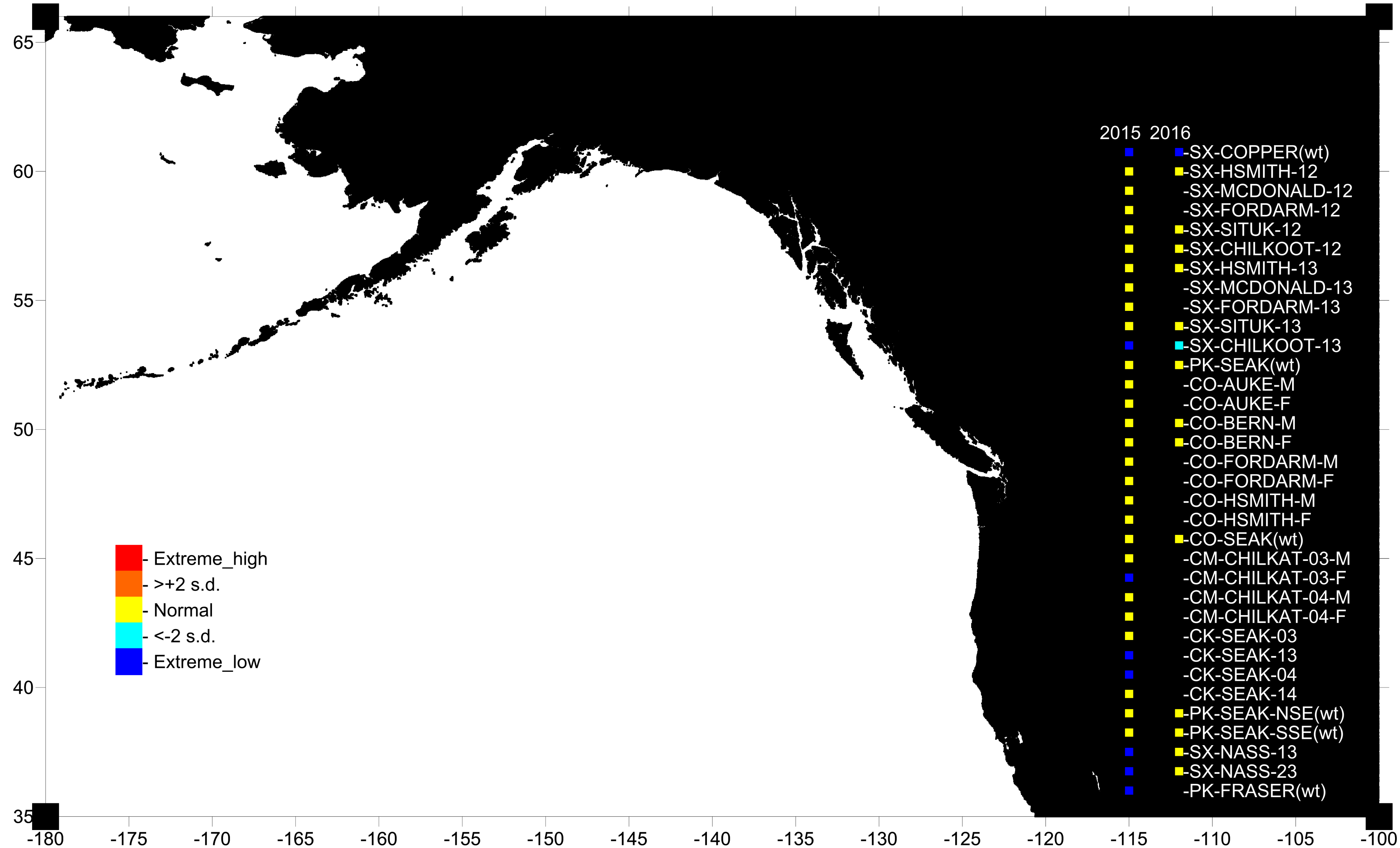

Illustration 1: Anomalies and extrema in mean size at age in 2015 and 2016; most are mean length but mean weight is indicated by (wt) in the label. SX-sockeye, PK-pink, CK-chinook, CO-coho, CM-chum, SH-steelhead. Age-at-maturity indicated as two numerals x.y where x-number of freshwater annuli and y-number of ocean annuli. Total age is their sum+1 as there is no annulus formed during the first winter in freshwater (as an egg).

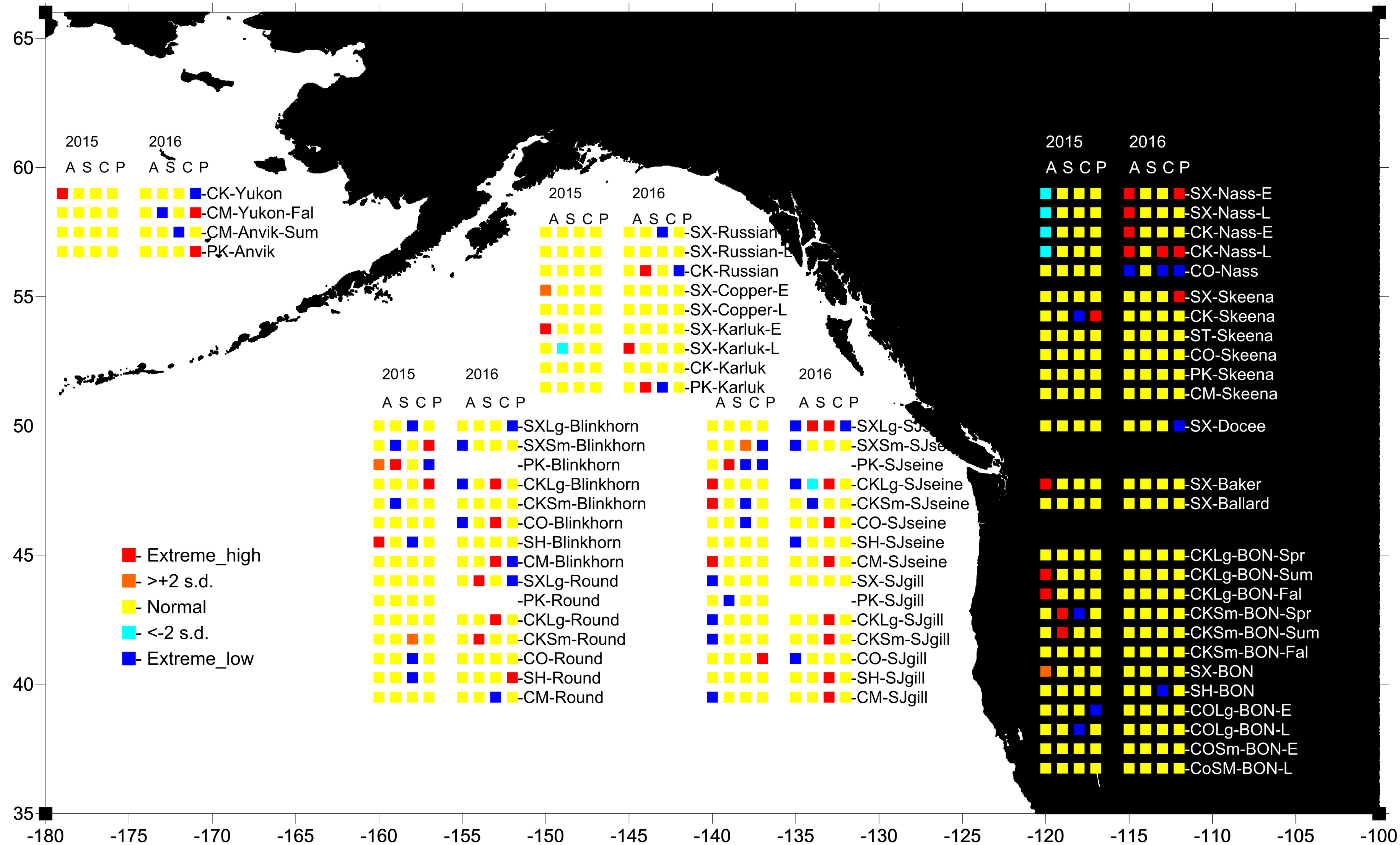

Illustration 2: Determination of extrema and strong anomalies in: A= abundance, S= skewness (high [low] values have an abrupt [slow] rise to a peak followed by a long [abrupt] decline), C= compression (high [low] values have a larger percentage of the run passing near the peak date), P= peak date.(high [low] values are late [early]).Lg= large adults, Sm= small adults, E= early run, L= late run, Spr= spring, Sum= summer, Fal= autumn. SX-sockeye, PK-pink, CK-chinook, CO-coho, CM-chum, SH-steelhead. Other location codes are SJ= San Juan, BON=Bonneville Dam.